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EPA's Map of Radon Zones

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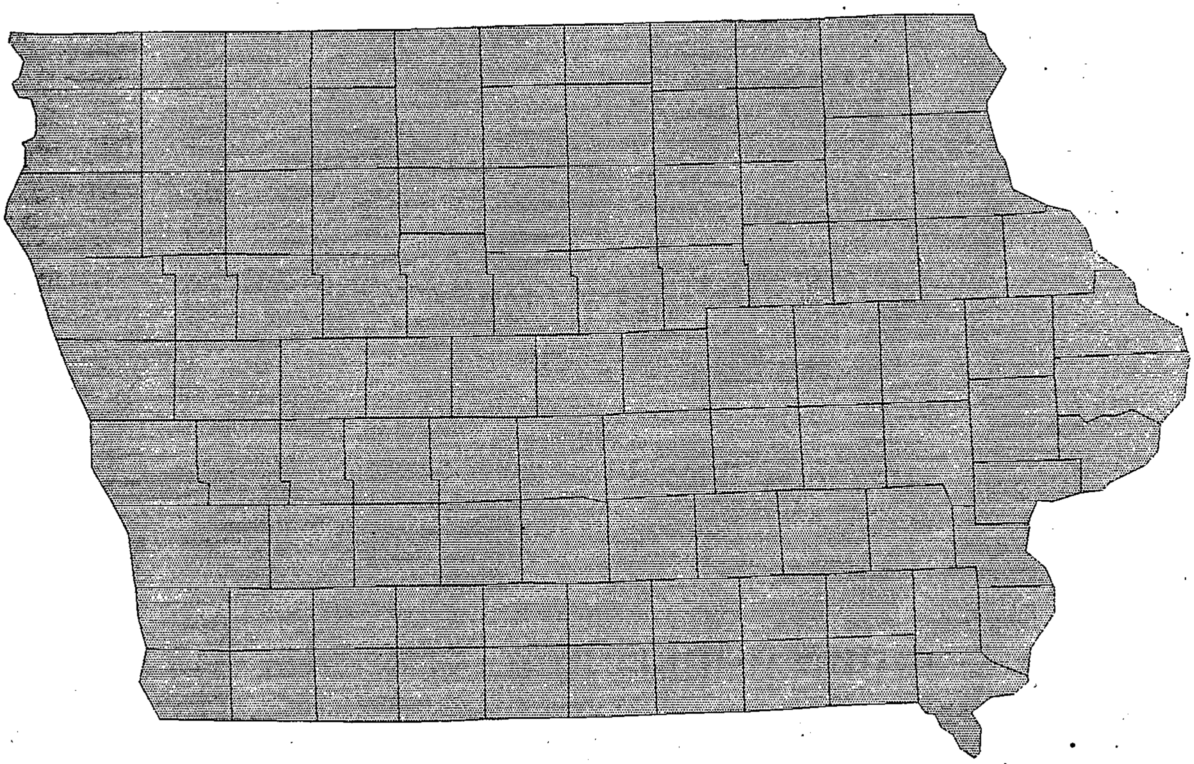

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IOWA

RADON DIVISION
OFFICE OF RADIATION AND INDOOR AIR
U.S. ENVIRONMENTAL PROTECTION AGENCY

SEPTEMBER, 1993

ACKNOWLEDGEMENTS

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OVERVIEW

Sections 307 and 309 of the 1988 Indoor Radon Abatement Act (IRAA) direct EPA to identify areas of the United States that have the potential to produce elevated levels of radon. EPA, the U.S. Geological Survey (USGS), and the Association of American State Geologists (AASG) have worked closely over the past several years to produce a series of maps and documents which address these directives. The EPA Map of Radon Zones is a compilation of that work and fulfills the requirements of sections 307 and 309 of IRAA. The Map of Radon Zones identifies, on a county-by-county basis, areas of the U.S. that have the highest potential for elevated indoor radon levels (greater than 4 pCi/L).

The Map of Radon Zones is designed to assist national, State and local governments and organizations to target their radon program activities and resources. It is also intended to help building code officials determine areas that are the highest priority for adopting radon-resistant building practices. The Map of Radon Zones should <u>not</u> be used to determine if individual homes in any given area need to be tested for radon. **EPA recommends that all homes be tested for radon, regardless of geographic location or the zone designation of the county in which they are located.**

This document provides background information concerning the development of the Map of Radon Zones. It explains the purposes of the map, the approach for developing the map (including the respective roles of EPA and USGS), the data sources used, the conclusions and confidence levels developed for the prediction of radon potential, and the review process that was conducted to finalize this effort.

BACKGROUND

Radon (Rn^{222}) is a colorless, odorless, radioactive gas. It comes from the natural decay of uranium that is found in nearly all soils. It typically moves through the ground to the air above and into homes and other buildings through cracks and openings in the foundation. Any home, school or workplace may have a radon problem, regardless of whether it is new or old, well-sealed or drafty, or with or without a basement. Nearly one out of every 15 homes in the U.S. is estimated to have elevated annual average levels of indoor radon.

Radon first gained national attention in early 1984, when extremely high levels of indoor radon were found in areas of Pennsylvania, New Jersey, and New York, along the Reading Prong-physiographic province. EPA established a Radon Program in 1985 to assist States and homeowners in reducing their risk of lung cancer from indoor radon.

Since 1985, EPA and USGS have been working together to continually increase our understanding of radon sources and the migration dynamics that cause elevated indoor radon levels. Early efforts resulted in the 1987 map entitled "Areas with Potentially High Radon Levels." This map was based on limited geologic information only because few indoor radon measurements were available at the time. The development of EPA's Map of Radon Zones and its technical foundation, USGS' National Geologic Radon Province Map, has been based on additional information from six years of the State/EPA Residential Radon Surveys, independent State residential surveys, and continued expansion of geologic and geophysical information, particularly the data from the National Uranium Resource Evaluation project.

Purpose of the Map of Radon Zones

EPA's Map of Radon Zones (Figure 1) assigns each of the 3141 counties in the United States to one of three zones:

- o Zone 1 counties have a predicted average indoor screening level > than 4 pCi/L
- o Zone 2 counties have a predicted average screening level ≥ 2 pCi/L and ≤ 4 pCi/L
- o Zone 3 counties have a predicted average screening level < 2 pCi/L

The Zone designations were determined by assessing five factors that are known to be important indicators of radon potential: indoor radon measurements, geology, aerial radioactivity, soil parameters, and foundation types.

The predictions of average screening levels in each of the Zones is an expression of radon potential in the lowest liveable area of a structure. This map is unable to estimate actual exposures to radon. EPA recommends methods for testing and fixing individual homes based on an estimate of actual exposure to radon. For more information on testing and fixing elevated radon levels in homes consult these EPA publications: *A Citizen's Guide to Radon, the Consumer's Guide to Radon Reduction and the Home Buyer's and Seller's Guide to Radon.*

EPA believes that States, local governments and other organizations can achieve optimal risk reductions by targeting resources and program activities to high radon potential areas. Emphasizing targeted approaches (technical assistance, information and outreach efforts, promotion of real estate mandates and policies and building codes, etc.) in such areas addresses the greatest potential risks first.

EPA also believes that the use of passive radon control systems in the construction of new homes in Zone 1 counties, and the activation of those systems if necessitated by follow-up testing, is a cost effective approach to achieving significant radon risk reduction.

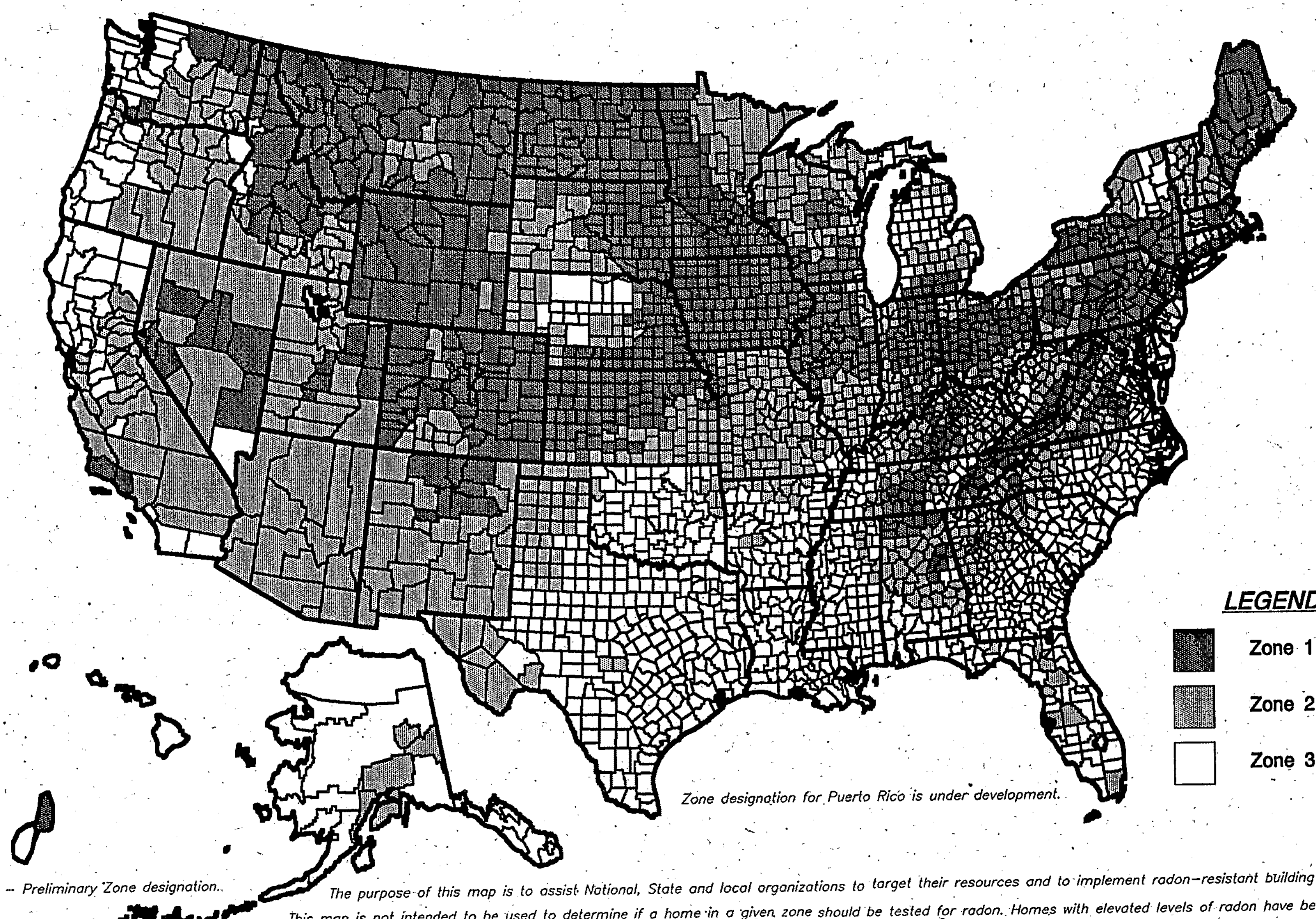
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in water.

Development of the Map of Radon Zones

The technical foundation for the Map of Radon Zones is the USGS Geologic Radon Province Map. In order to examine the radon potential for the United States, the USGS began by identifying approximately 360 separate geologic provinces for the U.S. The provinces are shown on the USGS Geologic Radon Province Map (Figure 2). Each of the geologic provinces was evaluated by examining the available data for that area: indoor radon measurements, geology, aerial radioactivity, soil parameters, and foundation types. As stated previously, these five factors are considered to be of basic importance in assessing radon

Figure 1

EPA Map of Radon Zones



The purpose of this map is to assist National, State and local organizations to target their resources and to implement radon-resistant building codes.

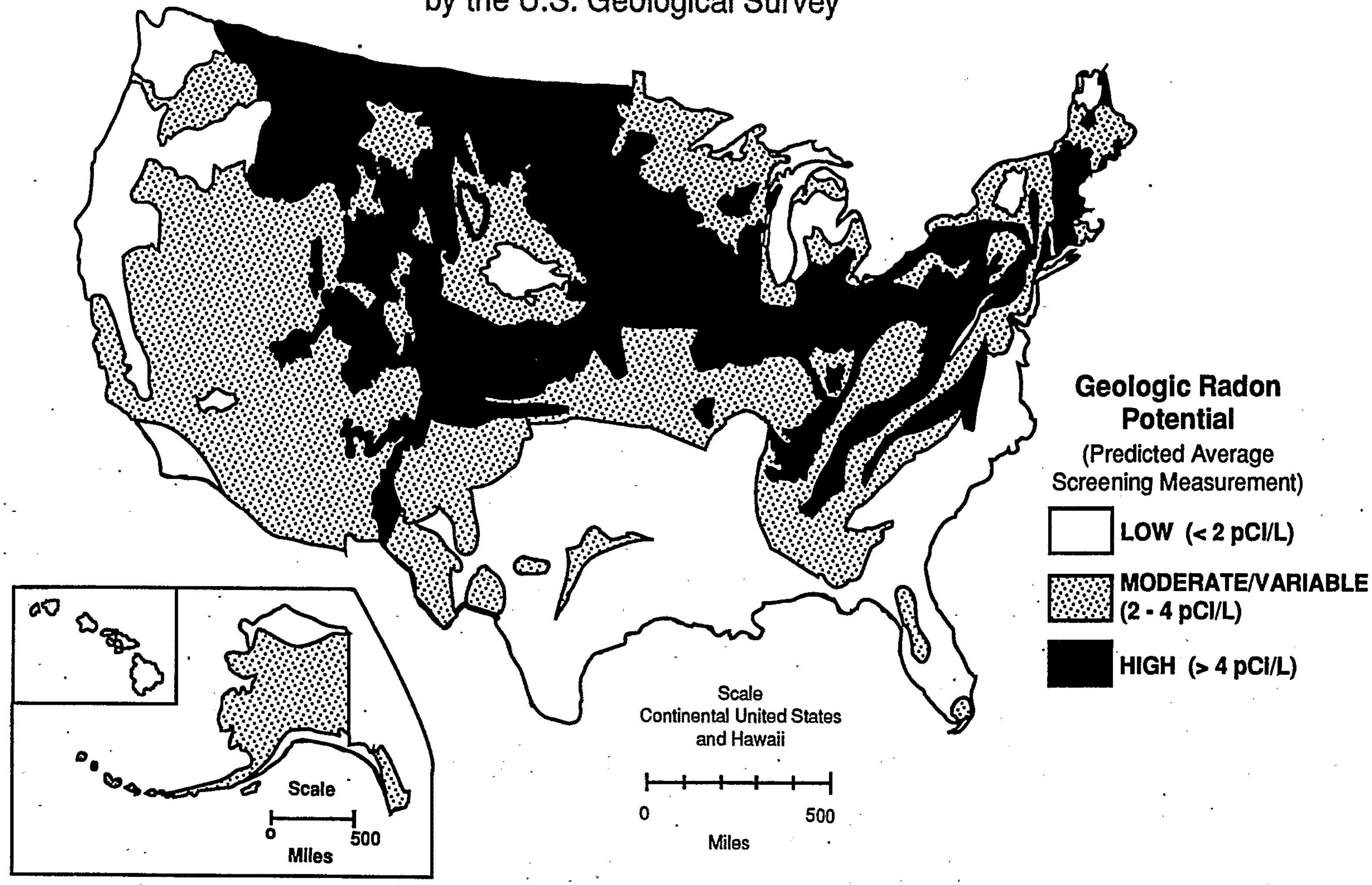
This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. All homes should be tested, regardless of geographic location.

__IMPORTANT:__ Consult the EPA Map of Radon Zones document (EPA–402–R–93–071) before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.

Figure 2

GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES

by the U.S. Geological Survey



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potential and some data are available for each of these factors in every geologic province. The province boundaries do not coincide with political borders (county and state) but define areas of general radon potential. The five factors were assigned numerical values based on an assessment of their respective contribution to radon potential, and a confidence level was assigned to each contributing variable. The approach used by USGS to estimate the radon potential for each province is described in Part II of this document.

EPA subsequently developed the Map of Radon Zones by extrapolating from the province level to the county level so that all counties in the U.S. were assigned to one of three radon zones. EPA assigned each county to a given zone based on its provincial radon potential. For example, if a county is located within a geologic province that has a predicted average screening level greater than 4 pCi/L, it was assigned to Zone 1. Likewise, counties located in provinces with predicted average screening levels ≥ 2 pCi/L and ≤ 4 pCi/L, and less than 2 pCi/L, were assigned to Zones 2 and 3, respectively.

If the boundaries of a county fall in more than one geologic province, the county was assigned to a zone based on the predicted radon potential of the province in which most of the area lies. For example, if three different provinces cross through a given county, the county was assigned to the zone representing the radon potential of the province containing most of the county's land area. (In this case, it is not technically correct to say that the predicted average screening level applies to the entire county since the county falls in multiple provinces with differing radon potentials.)

Figures 3 and 4 demonstrate an example of how EPA extrapolated the county zone designations for Nebraska from the USGS geologic province map for the State. As figure 3 shows, USGS has identified 5 geologic provinces for Nebraska. Most of the counties are extrapolated "straight" from their corresponding provinces, but there are counties "partitioned" by several provinces -- for example, Lincoln County. Although Lincoln county falls in multiple provinces, it was assigned to Zone 3 because most of its area falls in the province with the lowest radon potential.

It is important to note that EPA's extrapolation from the province level to the county level may mask significant "highs" and "lows" within specific counties. In other words, within-county variations in radon potential are not shown on the Map of Radon Zones. EPA recommends that users who may need to address specific within-county variations in radon potential (e.g., local government officials considering the implementation of radon-resistant construction codes) consult USGS' Geologic Radon Province Map and the State chapters provided with this map for more detailed information, as well as any locally available data.

Map Validation

The Map of Radon Zones is intended to represent a preliminary assessment of radon potential for the entire United States. The factors that are used in this effort --indoor radon data, geology, aerial radioactivity, soils, and foundation type -- are basic indicators for radon potential. It is important to note, however, that the map's county zone designations are not "statistically valid" predictions due to the nature of the data available for these 5 factors at the county level. In order to validate the map in light of this lack of statistical confidence, EPA conducted a number of analyses. These analyses have helped EPA to identify the best situations in which to apply the map, and its limitations.

Figure 3

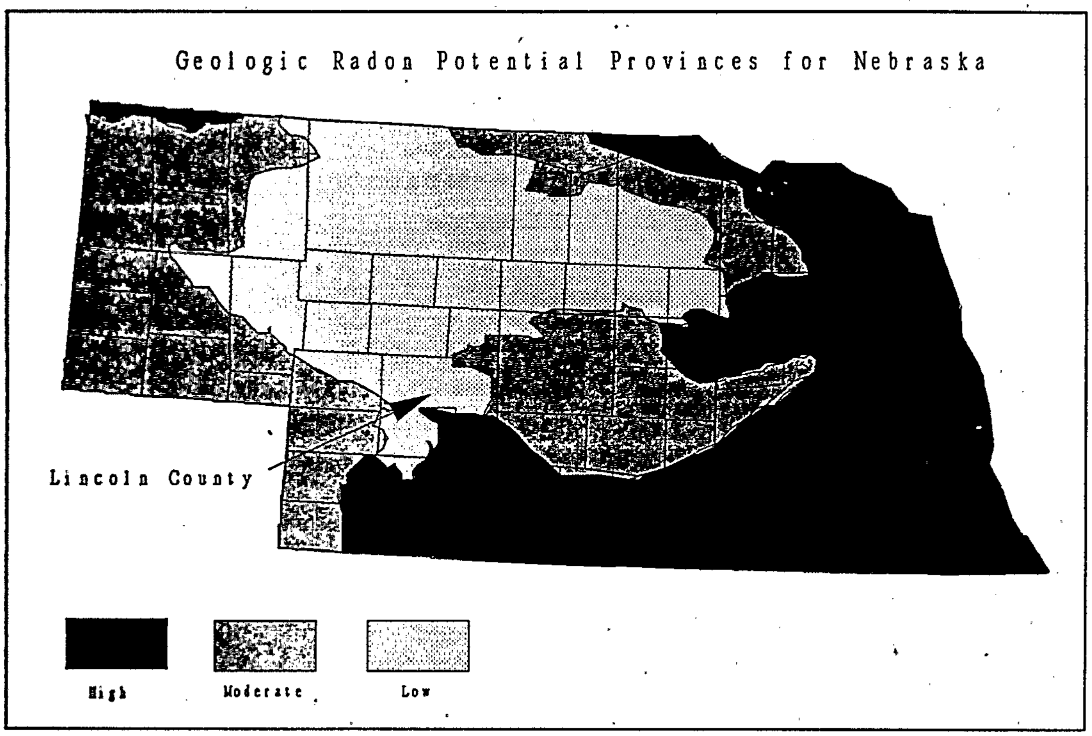
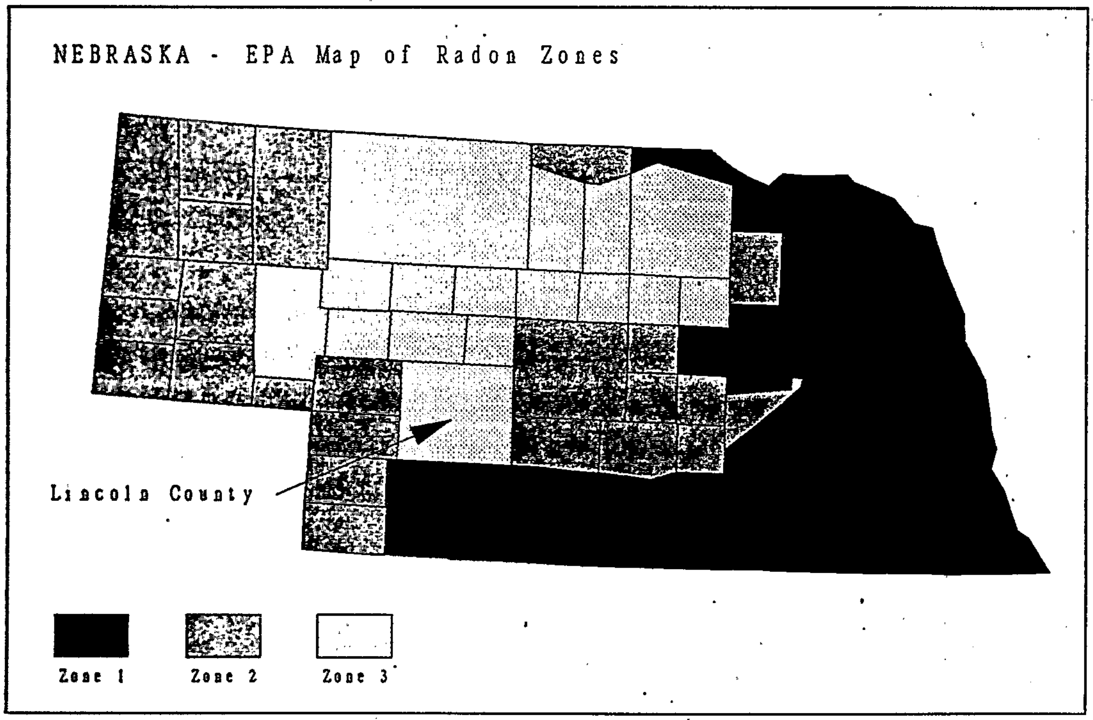


Figure 4



One such analysis involved comparing county zone designations to indoor radon measurements from the State/EPA Residential Radon Surveys (SRRS). Screening averages for counties with at least 100 measurements were compared to the counties' predicted radon potential as indicated by the Map of Radon Zones. EPA found that 72% of the county screening averages were correctly reflected by the appropriate zone designations on the Map. In all other cases, they only differed by 1 zone.

Another accuracy analysis used the annual average data from the National Residential Radon Survey (NRRS). The NRRS indicated that approximately 6 million homes in the United States have annual averages greater than or equal to 4 pCi/L. By cross checking the county location of the approximately 5,700 homes which participated in the survey, their radon measurements, and the zone designations for these counties, EPA found that approximately 3.8 million homes of the 5.4 million homes with radon levels greater than or equal to 4 pCi/L will be found in counties designated as Zone 1. A random sampling of an equal number of counties would have only found approximately 1.8 million homes greater than 4 pCi/L. In other words, this analysis indicated that the map approach is three times more efficient at identifying high radon areas than random selection of zone designations.

Together, these analyses show that the approach EPA used to develop the Map of Radon Zones is a reasonable one. In addition, the Agency's confidence is enhanced by results of the extensive State review process -- the map generally agrees with the States' knowledge of and experience in their own jurisdictions. However, the accuracy analyses highlight two important points: the fact that elevated levels will be found in Zones 2 and 3, and that there will be significant numbers of homes with lower indoor radon levels in all of the Zones. For these reasons, users of the Map of Radon Zones need to supplement the Map with locally available data whenever possible. Although all known "hot spots", i.e., localized areas of consistently elevated levels, are discussed in the State-specific chapters, accurately defining the boundaries of the "hot spots" on this scale of map is not possible at this time. Also, unknown "hot spots" do exist.

The Map of Radon Zones is intended to be a starting point for characterizing radon potential because our knowledge of radon sources and transport is always growing. Although this effort represents the best data available at this time, EPA will continue to study these parameters and others such as house construction, ventilation features and meteorology factors in order to better characterize the presence of radon in U.S homes, especially in high risk areas. These efforts will eventually assist EPA in refining and revising the conclusions of the Map of Radon Zones. And although this map is most appropriately used as a targeting tool by the aforementioned audiences -- **the Agency encourages all residents to test their homes for radon, regardless of geographic location or the zone designation of the county in which they live. Similarly, the Map of Radon Zones should not to be used in lieu of testing during real estate transactions.**

Review Process

The Map of Radon Zones has undergone extensive review within EPA and outside the Agency. The Association of American State Geologists (AASG) played an integral role in this review process. The AASG individual State geologists have reviewed their State-specific information, the USGS Geologic Radon Province Map, and other materials for their geologic content and consistency.

In addition to each State geologist providing technical comments, the State radon offices were asked to comment on their respective States' radon potential evaluations. In particular, the States were asked to evaluate the data used to assign their counties to specific zones. EPA and USGS worked with the States to resolve any issues concerning county zone designations. In a few cases, States have requested changes in county zone designations. The requests were based on additional data from the State on geology, indoor radon measurements, population, etc. Upon reviewing the data submitted by the States, EPA did make some changes in zone designations. These changes, which do not strictly follow the methodology outlined in this document, are discussed in the respective State chapters.

EPA encourages the States and counties to conduct further research and data collection efforts to refine the Map of Radon Zones. EPA would like to be kept informed of any changes the States, counties, or others make to the maps. Updates and revisions will be handled in a similar fashion to the way the map was developed. States should notify EPA of any proposed changes by forwarding the changes through the Regional EPA offices that are listed in Part II. Depending on the amount of new information that is presented, EPA will consider updating this map periodically. The State radon programs should initiate proper notification of the appropriate State officials when the Map of Radon Zones is released and when revisions or updates are made by the State or EPA.

THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by
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BACKGROUND

The Indoor Radon Abatement Act of 1988 (15 U.S.C. 2661-2671) directed the U.S. Environmental Protection Agency (EPA) to identify areas of the United States that have the potential to produce harmful levels of indoor radon. These characterizations were to be based on both geological data and on indoor radon levels in homes and other structures. The EPA also was directed to develop model standards and techniques for new building construction that would provide adequate prevention or mitigation of radon entry. As part of an Interagency Agreement between the EPA and the U.S. Geological Survey (USGS), the USGS has prepared radon potential estimates for the United States. This report is one of ten booklets that document this effort. The purpose and intended use of these reports is to help identify areas where states can target their radon program resources, to provide guidance in selecting the most appropriate building code options for areas, and to provide general information on radon and geology for each state for federal, state, and municipal officials dealing with radon issues. *These reports are not intended to be used as a substitute for indoor radon testing, and they cannot and should not be used to estimate or predict the indoor radon concentrations of individual homes, building sites, or housing tracts. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested for indoor radon.*

Booklets detailing the radon potential assessment for the U.S. have been developed for each State. USGS geologists are the authors of the geologic radon potential booklets. Each booklet consists of several components, the first being an overview to the mapping project (Part I), this introduction to the USGS assessment (Part II), including a general discussion of radon (occurrence, transport, etc.), and details concerning the types of data used. The third component is a summary chapter outlining the general geology and geologic radon potential of the EPA Region (Part III). The fourth component is an individual chapter for each state (Part IV). Each state chapter discusses the state's specific geographic setting, soils, geologic setting, geologic radon potential, indoor radon data, and a summary outlining the radon potential rankings of geologic areas in the state. A variety of maps are presented in each chapter—geologic, geographic, population, soils, aerial radioactivity, and indoor radon data by county. Finally, the booklets contain EPA's map of radon zones for each state and an accompanying description (Part V).

Because of constraints on the scales of maps presented in these reports and because the smallest units used to present the indoor radon data are counties, some generalizations have been made in order to estimate the radon potential of each area. Variations in geology, soil characteristics, climatic factors, homeowner lifestyles, and other factors that influence radon concentrations can be quite large within any particular geologic area, so these reports cannot be used to estimate or predict the indoor radon concentrations of individual homes or housing tracts. Within any area of a given geologic radon potential ranking, there are likely to be areas where the radon potential is lower or higher than that assigned to the area as a whole, especially in larger areas such as the large counties in some western states.

In each state chapter, references to additional reports related to radon are listed for the state, and the reader is urged to consult these reports for more detailed information. In most cases the best sources of information on radon for specific areas are state and local departments of health, state departments responsible for nuclear safety or environmental protection, and U.S. EPA regional offices. More detailed information on state or local geology may be obtained from the state geological surveys. Addresses and telephone numbers of state radon contacts, geological surveys, and EPA regional offices are listed in Appendix C at the end of this chapter.

RADON GENERATION AND TRANSPORT IN SOILS

Radon (^{222}Rn) is produced from the radioactive decay of radium (^{226}Ra), which is, in turn, a product of the decay of uranium (^{238}U) (fig. 1). The half-life of ^{222}Rn is 3.825 days. Other isotopes of radon occur naturally, but, with the exception of thoron (^{220}Rn), which occurs in concentrations high enough to be of concern in a few localized areas, they are less important in terms of indoor radon risk because of their extremely short half-lives and less common occurrence. In general, the concentration and mobility of radon in soil are dependent on several factors, the most important of which are the soil's radium content and distribution, porosity, permeability to gas movement, and moisture content. These characteristics are, in turn, determined by the soil's parent-material composition, climate, and the soil's age or maturity. If parent-material composition, climate, vegetation, age of the soil, and topography are known, the physical and chemical properties of a soil in a given area can be predicted.

As soils form, they develop distinct layers, or horizons, that are cumulatively called the soil profile. The A horizon is a surface or near-surface horizon containing a relative abundance of organic matter but dominated by mineral matter. Some soils contain an E horizon, directly below the A horizon, that is generally characterized by loss of clays, iron, or aluminum, and has a characteristically lighter color than the A horizon. The B horizon underlies the A or E horizon. Important characteristics of B horizons include accumulation of clays, iron oxides, calcium carbonate or other soluble salts, and organic matter complexes. In drier environments, a horizon may exist within or below the B horizon that is dominated by calcium carbonate, often called caliche or calcrete. This carbonate-cemented horizon is designated the K horizon in modern soil classification schemes. The C horizon underlies the B (or K) and is a zone of weathered parent material that does not exhibit characteristics of A or B horizons; that is, it is generally not a zone of leaching or accumulation. In soils formed in place from the underlying bedrock, the C horizon is a zone of unconsolidated, weathered bedrock overlying the unweathered bedrock.

The shape and orientation of soil particles (soil structure) control permeability and affect water movement in the soil. Soils with blocky or granular structure have roughly equivalent permeabilities in the horizontal and vertical directions, and air and water can infiltrate the soil relatively easily. However, in soils with platy structure, horizontal permeability is much greater than vertical permeability, and air and moisture infiltration is generally slow. Soils with prismatic or columnar structure have dominantly vertical permeability. Platy and prismatic structures form in soils with high clay contents. In soils with shrink-swell clays, air

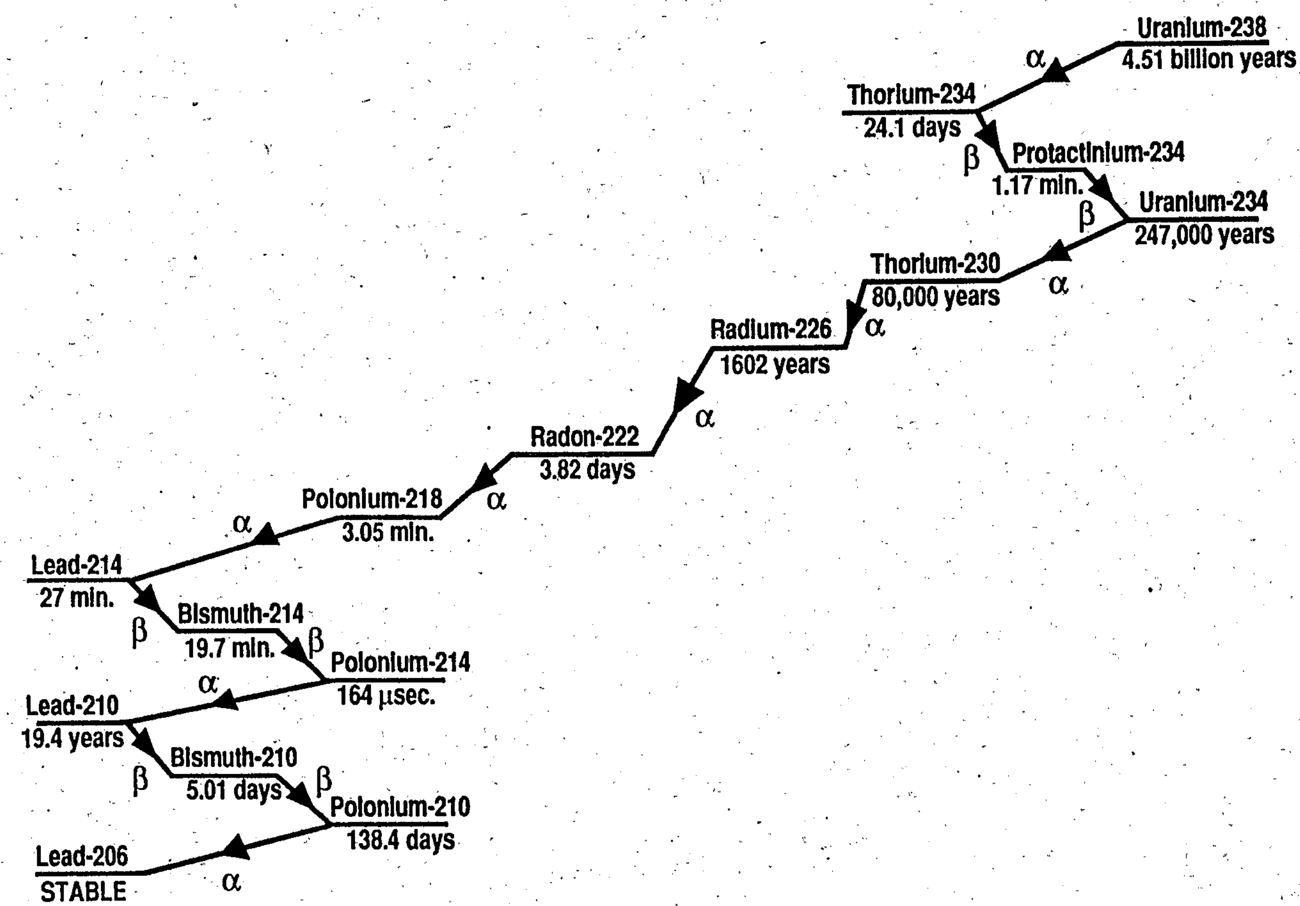

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

and moisture infiltration rates and depth of wetting may be limited when the cracks in the surface soil layers swell shut. Clay-rich B horizons, particularly those with massive or platy structure, can form a capping layer that impedes the escape of soil gas to the surface (Schumann and others, 1992). However, the shrinkage of clays can act to open or widen cracks upon drying, thus increasing the soil's permeability to gas flow during drier periods.

Radon transport in soils occurs by two processes: (1) diffusion and (2) flow (Tanner, 1964). Diffusion is the process whereby radon atoms move from areas of higher concentration to areas of lower concentration in response to a concentration gradient. Flow is the process by which soil air moves through soil pores in response to differences in pressure within the soil or between the soil and the atmosphere, carrying the radon atoms along with it. Diffusion is the dominant radon transport process in soils of low permeability, whereas flow tends to dominate in highly permeable soils (Sextro and others, 1987). In low-permeability soils, much of the radon may decay before it is able to enter a building because its transport rate is reduced. Conversely, highly permeable soils, even those that are relatively low in radium, such as those derived from some types of glacial deposits, have been associated with high indoor radon levels in Europe and in the northern United States (Akerblom and others, 1984; Kunz and others, 1989; Sextro and others, 1987). In areas of karst topography formed in carbonate rock (limestone or dolomite) environments, solution cavities and fissures can increase soil permeability at depth by providing additional pathways for gas flow.

Not all radium contained in soil grains and grain coatings will result in mobile radon when the radium decays. Depending on where the radium is distributed in the soil, many of the radon atoms may remain imbedded in the soil grain containing the parent radium atom, or become imbedded in adjacent soil grains. The portion of radium that releases radon into the pores and fractures of rocks and soils is called the emanating fraction. When a radium atom decays to radon, the energy generated is strong enough to send the radon atom a distance of about 40 nanometers (1 nm = 10^{-9} meters), or about 2×10^{-6} inches—this is known as alpha recoil (Tanner, 1980). Moisture in the soil lessens the chance of a recoiling radon atom becoming imbedded in an adjacent grain. Because water is more dense than air, a radon atom will travel a shorter distance in a water-filled pore than in an air-filled pore, thus increasing the likelihood that the radon atom will remain in the pore space. Intermediate moisture levels enhance radon emanation but do not significantly affect permeability. However, high moisture levels can significantly decrease the gas permeability of the soil and impede radon movement through the soil.

Concentrations of radon in soils are generally many times higher than those inside of buildings, ranging from tens of pCi/L to more than 100,000 pCi/L, but typically in the range of hundreds to low thousands of pCi/L. Soil-gas radon concentrations can vary in response to variations in climate and weather on hourly, daily, or seasonal time scales. Schumann and others (1992) and Rose and others (1988) recorded order-of-magnitude variations in soil-gas radon concentrations between seasons in Colorado and Pennsylvania. The most important factors appear to be (1) soil moisture conditions, which are controlled in large part by precipitation; (2) barometric pressure; and (3) temperature. Washington and Rose (1990) suggest that temperature-controlled partitioning of radon between water and gas in soil pores also has a significant influence on the amount of mobile radon in soil gas.

Homes in hilly limestone regions of the southern Appalachians were found to have higher indoor radon concentrations during the summer than in the winter. A suggested cause for this phenomenon involves temperature/pressure-driven flow of radon-laden air from subsurface solution cavities in the carbonate rock into houses. As warm air enters solution cavities that are higher on the hillslope than the homes, it cools and settles, pushing radon-laden air from lower in the cave or cavity system into structures on the hillslope (Gammage and others, 1993). In contrast, homes built over caves having openings situated below the level of the home had higher indoor radon levels in the winter, caused by cooler outside air entering the cave, driving radon-laden air into cracks and solution cavities in the rock and soil, and ultimately, into homes (Gammage and others, 1993).

RADON ENTRY INTO BUILDINGS

A driving force (reduced atmospheric pressure in the house relative to the soil, producing a pressure gradient) and entry points must exist for radon to enter a building from the soil. The negative pressure caused by furnace combustion, ventilation devices, and the stack effect (the rising and escape of warm air from the upper floors of the building, causing a temperature and pressure gradient within the structure) during cold winter months are common driving forces. Cracks and other penetrations through building foundations, sump holes, and slab-to-foundation wall joints are common entry points.

Radon levels in the basement are generally higher than those on the main floor or upper floors of most structures. Homes with basements generally provide more entry points for radon, commonly have a more pronounced stack effect, and typically have lower air pressure relative to the surrounding soil than nonbasement homes. The term "nonbasement" applies to slab-on-grade or crawl space construction.

METHODS AND SOURCES OF DATA

The assessments of radon potential in the booklets that follow this introduction were made using five main types of data: (1) geologic (lithologic); (2) aerial radiometric; (3) soil characteristics, including soil moisture, permeability, and drainage characteristics; (4) indoor radon data; and (5) building architecture (specifically, whether homes in each area are built slab-on-grade or have a basement or crawl space). These five factors were evaluated and integrated to produce estimates of radon potential. Field measurements of soil-gas radon or soil radioactivity were not used except where such data were available in existing, published reports of local field studies. Where applicable, such field studies are described in the individual state chapters.

GEOLOGIC DATA

The types and distribution of lithologic units and other geologic features in an assessment area are of primary importance in determining radon potential. Rock types that are most likely to cause indoor radon problems include carbonaceous black shales, glauconite-bearing sandstones, certain kinds of fluvial sandstones and fluvial sediments, phosphorites, chalk, karst-producing carbonate rocks, certain kinds of glacial deposits, bauxite, uranium-rich granitic rocks, metamorphic rocks of granitic composition, silica-rich volcanic rocks, many sheared or faulted rocks, some coals, and certain kinds of contact metamorphosed rocks. Rock types least likely to cause radon problems include marine quartz sands, non-carbonaceous shales and siltstones, certain kinds of clays, silica-poor metamorphic and igneous rocks, and basalts. Exceptions exist within these general lithologic groups because of the occurrence of localized uranium deposits, commonly of the hydrothermal type in crystalline rocks or the "roll-front" type in sedimentary rocks. Uranium and radium are commonly sited in heavy minerals, iron-oxide coatings on rock and soil grains, and organic materials in soils and sediments. Less common are uranium associated with phosphate and carbonate complexes in rocks and soils, and uranium minerals.

Although many cases of elevated indoor radon levels can be traced to high radium and (or) uranium concentrations in parent rocks, some structural features, most notably faults and shear zones, have been identified as sites of localized uranium concentrations (Deffeyes and MacGregor, 1980) and have been associated with some of the highest reported indoor radon levels (Gundersen, 1991). The two highest known indoor radon occurrences are associated with sheared fault zones in Boyertown, Pennsylvania (Gundersen and others, 1988a; Smith and others, 1987), and in Clinton, New Jersey (Henry and others, 1991; Muessig and Bell, 1988).

NURE Aerial Radiometric Data

Aerial radiometric data are used to quantify the radioactivity of rocks and soils. Equivalent uranium (eU) data provide an estimate of the surficial concentrations of radon parent materials (uranium, radium) in rocks and soils. Equivalent uranium is calculated from the counts received by a gamma-ray detector from the 1.76 MeV (mega-electron volts) emission energy corresponding to bismuth-214 (^{214}Bi), with the assumption that uranium and its decay products are in secular equilibrium. Equivalent uranium is expressed in units of parts per million (ppm). Gamma radioactivity also may be expressed in terms of a radium activity; 3 ppm eU corresponds to approximately 1 picocurie per gram (pCi/g) of radium-226. Although radon is highly mobile in soil and its concentration is affected by meteorological conditions (Kovach, 1945; Klusman and Jaacks, 1987; Schery and others, 1984; Schumann and others, 1992), statistical correlations between average soil-gas radon concentrations and average eU values for a wide variety of soils have been documented (Gundersen and others, 1988a, 1988b; Schumann and Owen, 1988). Aerial radiometric data can provide an estimate of radon source strength over a region, but the amount of radon that is able to enter a home from the soil is dependent on several local factors, including soil structure, grain size distribution, moisture content, and permeability, as well as type of house construction and its structural condition.

The aerial radiometric data used for these characterizations were collected as part of the Department of Energy National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s. The purpose of the NURE program was to identify and describe areas in the United States having potential uranium resources (U.S. Department of Energy, 1976). The NURE aerial radiometric data were collected by aircraft in which a gamma-ray spectrometer was mounted, flying approximately 122 m (400 ft) above the ground surface. The equivalent uranium maps presented in the state chapters were generated from reprocessed NURE data in which smoothing, filtering, recalibrating, and matching of adjacent quadrangle data sets were performed to compensate for background, altitude, calibration, and other types of errors and inconsistencies in the original data set (Duval and others, 1989). The data were then gridded and contoured to produce maps of eU with a pixel size corresponding to approximately 2.5 x 2.5 km (1.6 x 1.6 mi).

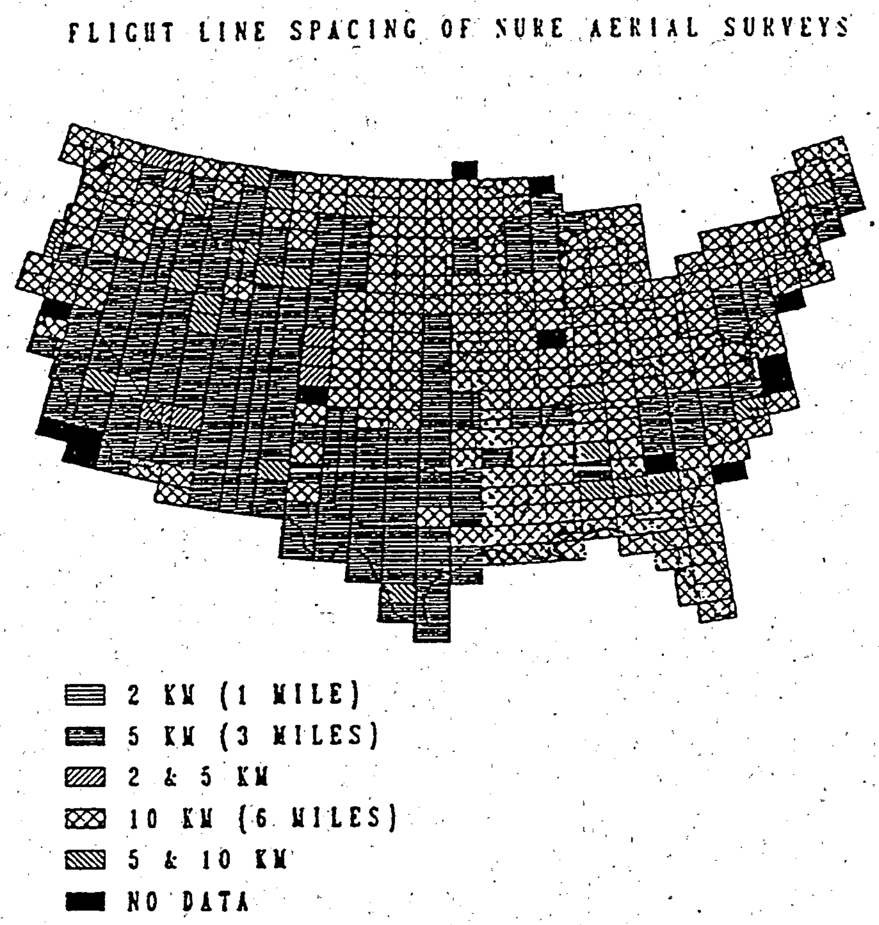

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

Figure 2 is an index map of NURE 1° x 2° quadrangles showing the flight-line spacing for each quadrangle. In general, the more closely spaced the flightlines are, the more area was covered by the aerial gamma survey, and thus, more detail is available in the data set. For an altitude of 400 ft above the ground surface and with primary flightline spacing typically between 3 and 6 miles, less than 10 percent of the ground surface of the United States was actually measured by the airborne gamma-ray detectors (Duval and others, 1989), although some areas had better coverage than others due to the differences in flight-line spacing between areas (fig. 2). This suggests that some localized uranium anomalies may not have been detected by the aerial surveys, but the good correlations of eU patterns with geologic outcrop patterns indicate that, at relatively small scales (approximately 1:1,000,000 or smaller) the National eU map (Duval and others, 1989) gives reasonably good estimates of average surface uranium concentrations and thus can assist in the prediction of radon potential of rocks and soils, especially when augmented with additional geologic and soil data.

The shallow (20-30 cm) depth of investigation of gamma-ray spectrometers, either ground-based or airborne (Duval and others, 1971; Durrance, 1986), suggests that gamma-ray data may sometimes underestimate the radon-source strength in soils in which some of the radionuclides in the near-surface soil layers have been transported downward through the soil profile. In such cases the concentration of radioactive minerals in the A horizon would be lower than in the B horizon, where such minerals are typically concentrated. The concentration of radionuclides in the C horizon and below may be relatively unaffected by surface solution processes. Under these conditions the surface gamma-ray signal may indicate a lower radon source concentration than actually exists in the deeper soil layers, which are most likely to affect radon levels in structures with basements. The redistribution of radionuclides in soil profiles is dependent on a combination of climatic, geologic, and geochemical factors. There is reason to believe that correlations of eU with actual soil radium and uranium concentrations at a depth relevant to radon entry into structures may be regionally variable (Duval, 1989; Schumann and Gundersen, 1991). Given sufficient understanding of the factors cited above, these regional differences may be predictable.

SOIL SURVEY DATA

Soil surveys prepared by the U.S. Soil Conservation Service (SCS) provide data on soil characteristics, including soil-cover thickness, grain-size distribution, permeability, shrink-swell potential, vegetative cover, generalized groundwater characteristics, and land use. The reports are available in county formats and State summaries. The county reports typically contain both generalized and detailed maps of soils in the area.

Because of time and map-scale constraints, it was impractical to examine county soil reports for each county in the United States, so more generalized summaries at appropriate scales were used where available. For State or regional-scale radon characterizations, soil maps were compared to geologic maps of the area, and the soil descriptions, shrink-swell potential, drainage characteristics, depth to seasonal high water table, permeability, and other relevant characteristics of each soil group noted. Technical soil terms used in soil surveys are generally complex; however, a good summary of soil engineering terms and the national distribution of technical soil types is the "Soils" sheet of the National Atlas (U.S. Department of Agriculture, 1987).

Soil permeability is commonly expressed in SCS soil surveys in terms of the speed, in inches per hour (in/hr), at which water soaks into the soil, as measured in a soil percolation test. Although in/hr are not truly units of permeability, these units are in widespread use and are referred to as "permeability" in SCS soil surveys The permeabilities listed in the SCS surveys are for water, but they generally correlate well with gas permeability. Because data on gas permeability of soils is extremely limited, data on permeability to water is used as a substitute except in cases in which excessive soil moisture is known to exist. Water in soil pores inhibits gas transport, so the amount of radon available to a home is effectively reduced by a high water table. Areas likely to have high water tables include river valleys, coastal areas, and some areas overlain by deposits of glacial origin (for example, loess).

Soil permeabilities greater than 6.0 in/hr may be considered high, and permeabilities less than 0.6 in/hr may be considered low in terms of soil-gas transport. Soils with low permeability may generally be considered to have a lower radon potential than more permeable soils with similar radium concentrations. Many well-developed soils contain a clay-rich B horizon that may impede vertical soil gas transport. Radon generated below this horizon cannot readily escape to the surface, so it would instead tend to move laterally, especially under the influence of a negative pressure exerted by a building.

Shrink-swell potential is an indicator of the abundance of smectitic (swelling) clays in a soil. Soils with a high shrink-swell potential may cause building foundations to crack, creating pathways for radon entry into the structure. During dry periods, desiccation cracks in shrink-swell soils provide additional pathways for soil-gas transport and effectively increase the gas permeability of the soil. Soil permeability data and soil profile data thus provide important information for regional radon assessments.

Indoor Radon Data

Two major sources of indoor radon data were used. The first and largest source of data is from the State/EPA Residential Radon Survey (Ronca-Battista and others, 1988; Dziuban and others, 1990). Forty-two states completed EPA-sponsored indoor radon surveys between 1986 and 1992 (fig. 3). The State/EPA Residential Radon Surveys were designed to be comprehensive and statistically significant at the state level, and were subjected to high levels of quality assurance and control. The surveys collected screening indoor radon measurements, defined as 2-7 day measurements using charcoal canister radon detectors placed in the lowest livable area of the home. The target population for the surveys included owner-occupied single-family, detached housing units (White and others, 1989), although attached structures such as duplexes, townhouses, or condominiums were included in some of the surveys if they met the other criteria and had contact with the ground surface. Participants were selected randomly from telephone-directory listings. In total, approximately 60,000 homes were tested in the State/EPA surveys.

The second source of indoor radon data comes from residential surveys that have been conducted in a specific state or region of the country (e.g. independent state surveys or utility company surveys). Several states, including Delaware, Florida, Illinois, New Hampshire, New Jersey, New York, Oregon, and Utah, have conducted their own surveys of indoor radon. The quality and design of a state or other independent survey are discussed and referenced where the data are used.

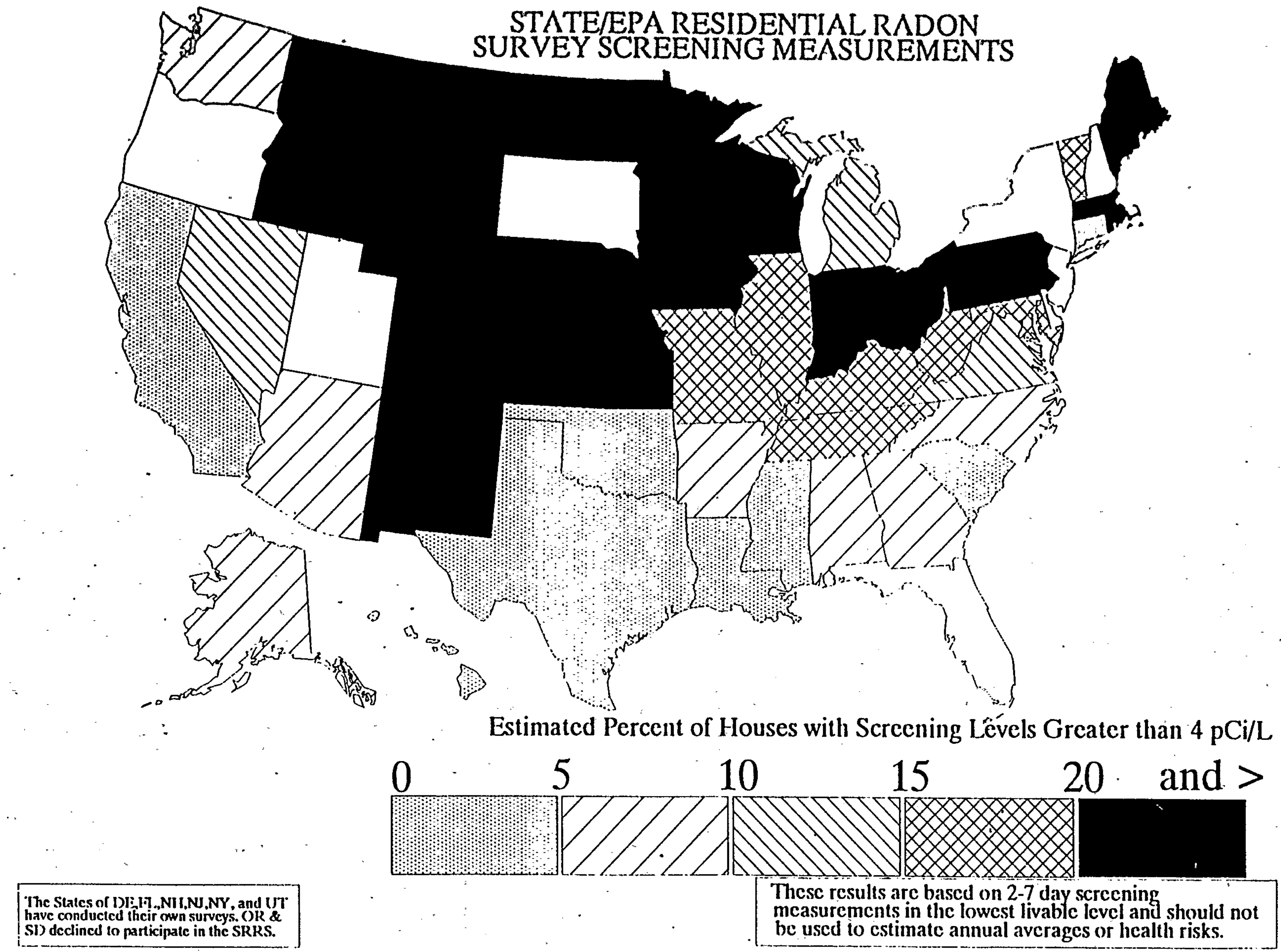

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

Data for only those counties with five or more measurements are shown in the indoor radon maps in the state chapters, although data for all counties with a nonzero number of measurements are listed in the indoor radon data tables in each state chapter. In total, indoor radon data from more than 100,000 homes nationwide were used in the compilation of these assessments. Radon data from State or regional indoor radon surveys, public health organizations, or other sources are discussed in addition to the primary data sources where they are available. Nearly all of the data used in these evaluations represent short-term (2-7 day) screening measurements from the lowest livable space of the homes. Specific details concerning the nature and use of indoor radon data sets other than the State/EPA Residential Radon Survey are discussed in the individual State chapters.

RADON INDEX AND CONFIDENCE INDEX

Many of the geologic methods used to evaluate an area for radon potential require subjective opinions based on the professional judgment and experience of the individual geologist. The evaluations are nevertheless based on established scientific principles that are universally applicable to any geographic area or geologic setting. This section describes the methods and conceptual framework used by the U.S. Geological Survey to evaluate areas for radon potential based on the five factors discussed in the previous sections. The scheme is divided into two basic parts, a Radon Index (RI), used to rank the general radon potential of the area, and the Confidence Index (CI), used to express the level of confidence in the prediction based on the quantity and quality of the data used to make the determination. This scheme works best if the areas to be evaluated are delineated by geologically-based boundaries (geologic provinces) rather than political ones (state/county boundaries) in which the geology may vary across the area.

Radon Index. Table 1 presents the Radon Index (RI) matrix. The five factors—indoor radon data, geology, aerial radioactivity, soil parameters, and house foundation type—were quantitatively ranked (using a point value of 1, 2, or 3) for their respective contribution to radon potential in a given area. At least some data for the 5 factors are consistently available for every geologic province. Because each of these main factors encompass a wide variety of complex and variable components, the geologists performing the evaluation relied heavily on their professional judgment and experience in assigning point values to each category and in determining the overall radon potential ranking. Background information on these factors is discussed in more detail in the preceding sections of this introduction.

Indoor radon was evaluated using unweighted arithmetic means of the indoor radon data for each geologic area to be assessed. Other expressions of indoor radon levels in an area also could have been used, such as weighted averages or annual averages, but these types of data were not consistently available for the entire United States at the time of this writing, or the schemes were not considered sufficient to provide a means of consistent comparison across all areas. For this report, charcoal-canister screening measurement data from the State/EPA Residential Radon Surveys and other carefully selected sources were used, as described in the preceding section. To maintain consistency, other indoor radon data sets (vendor, state, or other data) were not considered in scoring the indoor radon factor of the Radon Index if they were not randomly sampled or could not be statistically combined with the primary indoor radon data sets. However, these additional radon data sets can provide a means to further refine correlations between geologic factors and radon potential, so they are

TABLE 1. RADON INDEX MATRIX. "ppm eU" indicates parts per million of equivalent uranium, as indicated by NURE aerial radiometric data. See text discussion for details.

INCREASING RADON POTENTIAL →

FACTOR	POINT VALUE		
	1	2	3
INDOOR RADON (average)	< 2 pCi/L	2 - 4 pCi/L	> 4 pCi/L
AERIAL RADIOACTIVITY	< 1.5 ppm eU	1.5 - 2.5 ppm eU	> 2.5 ppm eU
GEOLOGY*	negative	variable	positive
SOIL PERMEABILITY	low	moderate	high
ARCHITECTURE TYPE	mostly slab	mixed	mostly basement

*GEOLOGIC FIELD EVIDENCE (GFE) POINTS: GFE points are assigned in addition to points for the "Geology" factor for specific, relevant geologic field studies. See text for details.

Geologic evidence supporting:	HIGH radon	+2 points
	MODERATE	+1 point
	LOW	-2 points
No relevant geologic field studies		0 points

SCORING:

Radon potential category	Point range	Probable average screening indoor radon for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	12-17 points	> 4 pCi/L

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

FACTOR	POINT VALUE		
	1	2	3
INDOOR RADON DATA	sparse/no data	fair coverage/quality	good coverage/quality
AERIAL RADIOACTIVITY	questionable/no data	glacial cover	no glacial cover
GEOLOGIC DATA	questionable	variable	proven geol. model
SOIL PERMEABILITY	questionable/no data	variable	reliable, abundant

SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

POSSIBLE RANGE OF POINTS = 4 to 12

included as supplementary information and are discussed in the individual State chapters. If the average screening indoor radon level for an area was less than 2 pCi/L, the indoor radon factor was assigned 1 point, if it was between 2 and 4 pCi/L, it was scored 2 points, and if the average screening indoor radon level for an area was greater than 4 pCi/L, the indoor radon factor was assigned 3 RI points.

Aerial radioactivity data used in this report are from the equivalent uranium map of the conterminous United States compiled from NURE aerial gamma-ray surveys (Duval and others, 1989). These data indicate the gamma radioactivity from approximately the upper 30 cm of rock and soil, expressed in units of ppm equivalent uranium. An approximate average value of eU was determined visually for each area and point values assigned based on whether the overall eU for the area falls below 1.5 ppm (1 point), between 1.5 and 2.5 ppm (2 points), or greater than 2.5 ppm (3 points).

The geology factor is complex and actually incorporates many geologic characteristics. In the matrix, "positive" and "negative" refer to the presence or absence and distribution of rock types known to have high uranium contents and to generate elevated radon in soils or indoors. Examples of "positive" rock types include granites, black shales, phosphatic rocks, and other rock types described in the preceding "geologic data" section. Examples of "negative" rock types include marine quartz sands and some clays. The term "variable" indicates that the geology within the region is variable or that the rock types in the area are known or suspected to generate elevated radon in some areas but not in others due to compositional differences, climatic effects, localizeddistribution of uranium, or other factors. Geologic information indicates not only how much uranium is present in the rocks and soils but also gives clues for predicting general radon emanation and mobility characteristics through additional factors such as structure (notably the presence of faults or shears) and geochemical characteristics (for example, a phosphate-rich sandstone will likely contain more uranium than a sandstone containing little or no phosphate because the phosphate forms chemical complexes with uranium). "Negative", "variable", and "positive" geology were assigned 1, 2, and 3 points, respectively.

In cases where additional reinforcing or contradictory geologic evidence is available, Geologic Field Evidence (GFE) points were added to or subtracted from an area's score (Table 1). Relevant geologic field studies are important to enhancing our understanding of how geologic processes affect radon distribution. In some cases, geologic models and supporting field data reinforced an already strong (high or low) score; in others, they provided important contradictory data. GFE points were applied for geologically-sound evidence that supports the prediction (but which may contradict one or more factors) on the basis of known geologic field studies in the area or in areas with geologic and climatic settings similar enough that they could be applied with full confidence. For example, areas of the Dakotas, Minnesota, and Iowa that are covered with Wisconsin-age glacial deposits exhibit a low aerial radiometric signature and score only one RI point in that category. However, data from geologic field studies in North Dakota and Minnesota (Schumann and others, 1991) suggest that eU is a poor predictor of geologic radon potential in this area because radionuclides have been leached from the upper soil layers but are present and possibly even concentrated in deeper soil horizons, generating significant soil-gas radon. This positive supporting field evidence adds two GFE points to the score, which helps to counteract the invalid conclusion suggested by the radiometric data. No GFE points are awarded if there are no documented field studies for the area.

"Soil permeability" refers to several soil characteristics that influence radon concentration and mobility, including soil type, grain size, structure, soil moisture, drainage, slope, and permeability. In the matrix, "low" refers to permeabilities less than about 0.6 in/hr; "high" corresponds to greater than about 6.0 in/hr, in U.S. Soil Conservation Service (SCS) standard soil percolation tests. The SCS data are for water permeability, which generally correlates well with the gas permeability of the soil except when the soil moisture content is very high. Areas with consistently high water tables were thus considered to have low gas permeability. "Low, "moderate", and "high" permeability were assigned 1, 2, and 3 points, respectively.

Architecture type refers to whether homes in the area have mostly basements (3 points), mostly slab-on-grade construction (1 point), or a mixture of the two. Split-level and crawl space homes fall into the "mixed" category (2 points). Architecture information is necessary to properly interpret the indoor radon data and produce geologic radon potential categories that are consistent with screening indoor radon data.

The overall RI for an area is calculated by adding the individual RI scores for the 5 factors, plus or minus GFE points, if any. The total RI for an area falls in one of three categories—low, moderate or variable, or high. The point ranges for the three categories were determined by examining the possible combinations of points for the 5 factors and setting rules such that a majority (3 of 5 factors) would determine the final score for the low and high categories, with allowances for possible deviation from an ideal score by the other two factors. The moderate/variable category lies between these two ranges. A total deviation of 3 points from the "ideal" score was considered reasonable to allow for natural variability of factors—if two of the five factors are allowed to vary from the "ideal" for a category, they can differ by a minimum of 2 (1 point different each) and a maximum of 4 points (2 points different each). With "ideal" scores of 5, 10, and 15 points describing low, moderate, and high geologic radon potential, respectively, an ideal low score of 5 points plus 3 points for possible variability allows a maximum of 8 points in the low category. Similarly, an ideal high score of 15 points minus 3 points gives a minimum of 12 points for the high category. Note, however, that if both other factors differ by two points from the "ideal", indicating considerable variability in the system, the total point score would lie in the adjacent (i.e., moderate/variable) category.

Confidence Index. Except for architecture type, the same factors were used to establish a Confidence Index (CI) for the radon potential prediction for each area (Table 2). Architecture type was not included in the confidence index because house construction data are readily and reliably available through surveys taken by agencies and industry groups including the National Association of Home Builders, U.S. Department of Housing and Urban Development, and the Federal Housing Administration; thus it was not considered necessary to question the quality or validity of these data. The other factors were scored on the basis of the quality and quantity of the data used to complete the RI matrix.

Indoor radon data were evaluated based on the distribution and number of data points and on whether the data were collected by random sampling (State/EPA Residential Radon Survey or other state survey data) or volunteered vendor data (likely to be nonrandom and biased toward population centers and/or high indoor radon levels). The categories listed in the CI matrix for indoor radon data ("sparse or no data", "fair coverage or quality", and "good coverage/quality") indicate the sampling density and statistical robustness of an indoor radon data set. Data from the State/EPA Residential Radon Survey and statistically valid state surveys were typically assigned 3 Confidence Index points unless the data were poorly distributed or absent in the area evaluated.

Aerial radioactivity data are available for all but a few areas of the continental United States and for part of Alaska. An evaluation of the quality of the radioactivity data was based on whether there appeared to be a good correlation between the radioactivity and the actual amount of uranium or radium available to generate mobile radon in the rocks and soils of the area evaluated. In general, the greatest problems with correlations among eU, geology, and soil-gas or indoor radon levels were associated with glacial deposits (see the discussion in a previous section) and typically were assigned a 2-point Confidence Index score. Correlations among eU, geology, and radon were generally sound in unglaciated areas and were usually assigned 3 CI points. Again, however, radioactivity data in some unglaciated areas may have been assigned fewer than 3 points, and in glaciated areas may be assigned only one point, if the data were considered questionable or if coverage was poor.

To assign Confidence Index scores for the geologic data factor, rock types and geologic settings for which a physical-chemical, process-based understanding of radon generation and mobility exists were regarded as having "proven geologic models" (3 points); a high confidence could be held for predictions in such areas. Rocks for which the processes are less well known or for which data are contradictory were regarded as "variable" (2 points), and those about which little is known or for which no apparent correlations have been found were deemed "questionable" (1 point).

The soil permeability factor was also scored based on quality and amount of data. The three categories for soil permeability in the Confidence Index are similar in concept, and scored similarly, to those for the geologic data factor. Soil permeability can be roughly estimated from grain size and drainage class if data from standard, accepted soil percolation tests are unavailable; however, the reliability of the data would be lower than if percolation test figures or other measured permeability data are available, because an estimate of this type does not encompass all the factors that affect soil permeability and thus may be inaccurate in some instances. Most published soil permeability data are for water; although this is generally closely related to the air permeability of the soil, there are some instances when it may provide an incorrect estimate. Examples of areas in which water permeability data may not accurately reflect air permeability include areas with consistently high levels of soil moisture, or clay-rich soils, which would have a low water permeability but may have a significantly higher air permeability when dry due to shrinkage cracks in the soil. These additional factors were applied to the soil permeability factor when assigning the RI score, but may have less certainty in some cases and thus would be assigned a lower CI score.

The Radon Index and Confidence Index give a general indication of the relative contributions of the interrelated geologic factors influencing radon generation and transport in rocks and soils, and thus, of the potential for elevated indoor radon levels to occur in a particular area. However, because these reports are somewhat generalized to cover relatively large areas of States, it is highly recommended that more detailed studies be performed in local areas of interest, using the methods and general information in these booklets as a guide.

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APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma) [1]
Eon or Eonothem	**Era or Erathem**	**Period, System, Subperiod, Subsystem**		**Epoch or Series**		
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010
				Pleistocene		1.6 (1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene[2] Subperiod or Subsystem (Pɛ)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		66 (63–66)
	Mesozoic[2] (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late	Upper	
				Middle	Middle	
				Early	Lower	205 (200–215)
		Triassic (TR)		Late	Upper	
				Middle	Middle	
				Early	Lower	~240
	Paleozoic[2] (Pz)	Permian (P)		Late	Upper	
				Early	Lower	290 (290–305)
		Carboniferous Systems (C)	Pennsylvanian (₱)	Late	Upper	
				Middle	Middle	
				Early	Lower	~330
			Mississippian (M)	Late	Upper	
				Early	Lower	360 (360–365)
		Devonian (D)		Late	Upper	
				Middle	Middle	
				Early	Lower	410 (405–415)
		Silurian (S)		Late	Upper	
				Middle	Middle	
				Early	Lower	435 (435–440)
		Ordovician (O)		Late	Upper	
				Middle	Middle	
				Early	Lower	500 (495–510)
		Cambrian (Є)		Late	Upper	
				Middle	Middle	
				Early	Lower	~570 [3]
Proterozoic (P)	Late Proterozoic (Z)	None defined				900
	Middle Proterozoic (Y)	None defined				1600
	Early Proterozoic (X)	None defined				2500
Archean (A)	Late Archean (W)	None defined				3000
	Middle Archean (V)	None defined				3400
	Early Archean (U)	None defined				3800 ?
pre-Archean (pA) [4]						

[1] Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age boundaries not closely bracketed by existing data shown by ~. Decay constants and isotopic ratios employed are cited in Steiger and Jäger (1977). Designation m.y. used for an interval of time.

[2] Modifiers (lower, middle, upper or early, middle, late) when used with these items are informal divisions of the larger unit; the first letter of the modifier is lowercase.

[3] Rocks older than 570 Ma also called Precambrian (p-Є), a time term without specific rank.

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

pCi/L (picocuries per liter)- a unit of measure of radioactivity used to describe radon concentrations in a volume of air. One picocurie (10^{-12} curies) is equal to about 2.2 disintegrations of radon atoms per minute. A liter is about 1.06 quarts. The average concentration of radon in U.S. homes measured to date is between 1 and 2 pCi/L.

Bq/m³ (Becquerels per cubic meter)- a metric unit of radioactivity used to describe radon concentrations in a volume of air. One becquerel is equal to one radioactive disintegration per second. One pCi/L is equal to 37 Bq/m^3.

ppm (parts per million)- a unit of measure of concentration by weight of an element in a substance, in this case, soil or rock. One ppm of uranium contained in a ton of rock corresponds to about 0.03 ounces of uranium. The average concentration of uranium in soils in the United States is between 1 and 2 ppm.

in/hr (inches per hour)- a unit of measure used by soil scientists and engineers to describe the permeability of a soil to water flowing through it. It is measured by digging a hole 1 foot (12 inches) square and one foot deep, filling it with water, and measuring the time it takes for the water to drain from the hole. The drop in height of the water level in the hole, measured in inches, is then divided by the time (in hours) to determine the permeability. Soils range in permeability from less than 0.06 in/hr to greater than 20 in/hr, but most soils in the United States have permeabilities between these two extremes.

Geologic terms and terms related to the study of radon

aerial radiometric, aeroradiometric survey A survey of radioactivity, usually gamma rays, taken by an aircraft carrying a gamma-ray spectrometer pointed at the ground surface.

alluvial fan A low, widespread mass of loose rock and soil material, shaped like an open fan and deposited by a stream at the point where it flows from a narrow mountain valley out onto a plain or broader valley. May also form at the junction with larger streams or when the gradient of the stream abruptly decreases.

alluvium, alluvial General terms referring to unconsolidated detrital material deposited by a stream or other body of running water.

alpha-track detector A passive radon measurement device consisting of a plastic film that is sensitive to alpha particles. The film is etched with acid in a laboratory after it is exposed. The etching reveals scratches, or "tracks", left by the alpha particles resulting from radon decay , which can then be counted to calculate the radon concentration. Useful for long-term (1-12 months) radon tests.

amphibolite A mafic metamorphic rock consisting mainly of pyroxenes and(or) amphibole and plagioclase.

argillite, argillaceous Terms referring to a rock derived from clay or shale, or any sedimentary rock containing an appreciable amount of clay-size material, i.e., argillaceous sandstone.

arid Term describing a climate characterized by dryness, or an evaporation rate that exceeds the amount of precipitation.

basalt A general term for a dark-colored mafic igneous rocks that may be of extrusive origin, such as volcanic basalt flows, or intrusive origin, such as basalt dikes.

batholith A mass of plutonic igneous rock that has more than 40 square miles of surface exposure and no known bottom.

carbonate A sedimentary rock consisting of the carbonate (CO_3) compounds of calcium, magnesium, or iron, e.g. limestone and dolomite.

carbonaceous Said of a rock or sediment that is rich in carbon, is coaly, or contains organic matter.

charcoal canister A passive radon measurement device consisting of a small container of granulated activated charcoal that is designed to adsorb radon. Useful for short duration (2-7 days) measurements only. May be referred to as a "screening" test.

chert A hard, extremely dense sedimentary rock consisting dominantly of interlocking crystals of quartz. Crystals are not visible to the naked eye, giving the rock a milky, dull luster. It may be white or gray but is commonly colored red, black, yellow, blue, pink, brown, or green.

clastic pertaining to a rock or sediment composed of fragments that are derived from preexisting rocks or minerals. The most common clastic sedimentary rocks are sandstone and shale.

clay A rock containing clay mineral fragments or material of any composition having a diameter less than 1/256 mm.

clay mineral One of a complex and loosely defined group of finely crystalline minerals made up of water, silicate and aluminum (and a wide variety of other elements). They are formed chiefly by alteration or weathering of primary silicate minerals. Certain clay minerals are noted for their small size and ability to absorb substantial amounts of water, causing them to swell. The change in size that occurs as these clays change between dry and wet is referred to as their **"shrink-swell"** potential.

concretion A hard, compact mass of mineral matter, normally subspherical but commonly irregular in shape; formed by precipitation from a water solution about a nucleus or center, such as a leaf, shell, bone, or fossil, within a sedimentary or fractured rock.

conglomerate A coarse-grained, clastic sedimentary rock composed of rock and mineral fragments larger than 2 mm, set in a finer-grained matrix of clastic material.

cuesta A hill or ridge with a gentle slope on one side and a steep slope on the other. The formation of a cuesta is controlled by the different weathering properties and the structural dip of the rocks forming the hill or ridge.

daughter product A nuclide formed by the disintegration of a radioactive precursor or "parent" atom.

delta, deltaic Referring to a low, flat, alluvial tract of land having a triangular or fan shape, located at or near the mouth of a river. It results from the accumulation of sediment deposited by a river at the point at which the river loses its ability to transport the sediment, commonly where a river meets a larger body of water such as a lake or ocean.

dike A tabular igneous intrusion of rock, younger than the surrounding rock, that commonly cuts across the bedding or foliation of the rock it intrudes.

diorite A plutonic igneous rock that is medium in color and contains visible dark minerals that make up less than 50% of the rock. It also contains abundant sodium plagioclase and minor quartz.

dolomite A carbonate sedimentary rock of which more than 50% consists of the mineral dolomite ($CaMg(CO_3)_2$), and is commonly white, gray, brown, yellow, or pinkish in color.

drainage The manner in which the waters of an area pass, flow off of, or flow into the soil. Also refers to the water features of an area, such as lakes and rivers, that drain it.

eolian Pertaining to sediments deposited by the wind.

esker A long, narrow, steep-sided ridge composed of irregular beds of sand and gravel deposited by streams beneath a glacier and left behind when the ice melted.

evapotranspiration Loss of water from a land area by evaporation from the soil and transpiration from plants.

extrusive Said of igneous rocks that have been erupted onto the surface of the Earth.

fault A fracture or zone of fractures in rock or sediment along which there has been movement.

fluvial, fluvial deposit Pertaining to sediment that has been deposited by a river or stream.

foliation A linear feature in a rock defined by both mineralogic and structural characteristics. It may be formed during deformation or metamorphism.

formation A mappable body of rock having similar characteristics.

glacial deposit Any sediment transported and deposited by a glacier or processes associated with glaciers, such as glaciofluvial sediments deposited by streams flowing from melting glaciers.

gneiss A rock formed by metamorphism in which bands and lenses of minerals of similar composition alternate with bands and lenses of different composition, giving the rock a striped or "foliated" appearance.

granite Broadly applied, any coarsely crystalline, quartz- and feldspar-bearing igneous plutonic rock. Technically, granites have between 10 and 50% quartz, and alkali feldspar comprises at least 65% of the total feldspar.

gravel An unconsolidated, natural accumulation of rock fragments consisting predominantly of particles greater than 2 mm in size.

heavy minerals Mineral grains in sediment or sedimentary rock having higher than average specific gravity. May form layers and lenses because of wind or water sorting by weight and size and may be referred to as a "placer deposit." Some heavy minerals are magnetite, garnet, zircon, monazite, and xenotime.

igneous Said of a rock or mineral that solidified from molten or partly molten rock material. It is one of the three main classes into which rocks are divided, the others being sedimentary and metamorphic.

intermontane A term that refers to an area between two mountains or mountain ranges.

intrusion, intrusive The processes of emplacement or injection of molten rock into pre-existing rock. Also refers to the rock formed by intrusive processes, such as an "intrusive igneous rock".

kame A low mound, knob, hummock, or short irregular ridge formed by a glacial stream at the margin of a melting glacier; composed of bedded sand and gravel.

karst terrain A type of topography that is formed on limestone, gypsum and other rocks by dissolution of the rock by water, forming sinkholes and caves.

lignite A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

limestone A carbonate sedimentary rock consisting of more than 50% calcium carbonate, primarily in the form of the mineral calcite ($CaCO_3$).

lithology The description of rocks in hand specimen and in outcrop on the basis of color, composition, and grain size.

loam A permeable soil composed of a mixture of relatively equal parts clay, silt, and sand, and usually containing some organic matter.

loess A fine-grained eolian deposit composed of silt-sized particles generally thought to have been deposited from windblown dust of Pleistocene age.

mafic Term describing an igneous rock containing more than 50% dark-colored minerals.

marine Term describing sediments deposited in the ocean, or precipitated from ocean waters.

metamorphic Any rock derived from pre-existing rocks by mineralogical, chemical, or structural changes in response to changes in temperature, pressure, stress, and the chemical environment. Phyllite, schist, amphibolite, and gneiss are metamorphic rocks.

moraine A mound, ridge, or other distinct accumulation of unsorted, unbedded glacial material, predominantly till, deposited by the action of glacial ice.

outcrop That part of a geologic formation or structure that appears at the surface of the Earth, as in "rock outcrop".

percolation test A term used in engineering for a test to determine the water permeability of a soil. A hole is dug and filled with water and the rate of water level decline is measured.

permeability The capacity of a rock, sediment, or soil to transmit liquid or gas.

phosphate, phosphatic, phosphorite Any rock or sediment containing a significant amount of phosphate minerals, i.e., minerals containing PO_4.

physiographic province A region in which all parts are similar in geologic structure and climate, which has had a uniform geomorphic history, and whose topography or landforms differ significantly from adjacent regions.

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

rhyolite An extrusive igneous rock of volcanic origin, compositionally equivalent to granite.

sandstone A clastic sedimentary rock composed of sand-sized rock and mineral material that is more or less firmly cemented. Sand particles range from 1/16 to 2 mm in size.

schist A strongly foliated crystalline rock, formed by metamorphism, that can be readily split into thin flakes or slabs. Contains mica; minerals are typically aligned.

screening level Result of an indoor radon test taken with a charcoal canister or similar device, for a short period of time, usually less than seven days. May indicate the potential for an indoor radon problem but does not indicate annual exposure to radon.

sediment Deposits of rock and mineral particles or fragments originating from material that is transported by air, water or ice, or that accumulate by natural chemical precipitation or secretion of organisms.

semiarid Refers to a climate that has slightly more precipitation than an arid climate.

shale A fine-grained sedimentary rock formed from solidification (lithification) of clay or mud.

shear zone Refers to a roughly linear zone of rock that has been faulted by ductile or non-ductile processes in which the rock is sheared and both sides are displaced relative to one another.

shrink-swell clay See clay mineral.

siltstone A fine-grained clastic sedimentary rock composed of silt-sized rock and mineral material and more or less firmly cemented. Silt particles range from 1/16 to 1/256 mm in size.

sinkhole A roughly circular depression in a karst area measuring meters to tens of meters in diameter. It is funnel shaped and is formed by collapse of the surface material into an underlying void created by the dissolution of carbonate rock.

slope An inclined part of the earth's surface.

solution cavity A hole, channel or cave-like cavity formed by dissolution of rock.

stratigraphy The study of rock strata; also refers to the succession of rocks of a particular area.

surficial materials Unconsolidated glacial, wind-, or waterborne deposits occurring on the earth's surface.

tablelands General term for a broad, elevated region with a nearly level surface of considerable extent.

terrace gravel Gravel-sized material that caps ridges and terraces, left behind by a stream as it cuts down to a lower level.

terrain A tract or region of the Earth's surface considered as a physical feature or an ecological environment.

till Unsorted, generally unconsolidated and unbedded rock and mineral material deposited directly adjacent to and underneath a glacier, without reworking by meltwater. Size of grains varies greatly from clay to boulders.

uraniferous Containing uranium, usually more than 2 ppm.

vendor data Used in this report to refer to indoor radon data collected and measured by commercial vendors of radon measurement devices and/or services.

volcanic Pertaining to the activities, structures, and extrusive rock types of a volcano.

water table The surface forming the boundary between the zone of saturation and the zone of aeration; the top surface of a body of unconfined groundwater in rock or soil.

weathering The destructive process by which earth and rock materials, on exposure to atmospheric elements, are changed in color, texture, composition, firmness, or form with little or no transport of the material.

APPENDIX C
EPA REGIONAL OFFICES

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EPA Region 5 (5AR26)
77 West Jackson Blvd.
Chicago, IL 60604-3507
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EPA Region 6 (6T-AS)
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EPA Region 7
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Kansas City, KS 66101
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State	EPA Region
Alabama	4
Alaska	10
Arizona	9
Arkansas	6
California	9
Colorado	8
Connecticut	1
Delaware	3
District of Columbia	3
Florida	4
Georgia	4
Hawaii	9
Idaho	10
Illinois	5
Indiana	5
Iowa	7
Kansas	7
Kentucky	4
Louisiana	6
Maine	1
Maryland	3
Massachusetts	1
Michigan	5
Minnesota	5
Mississippi	4
Missouri	7
Montana	8
Nebraska	7
Nevada	9
New Hampshire	1
New Jersey	2
New Mexico	6
New York	2
North Carolina	4
North Dakota	8
Ohio	5
Oklahoma	6
Oregon	10
Pennsylvania	3
Rhode Island	1
South Carolina	4
South Dakota	8
Tennessee	4
Texas	6
Utah	8
Vermont	1
Virginia	3
Washington	10
West Virginia	3
Wisconsin	5
Wyoming	8

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May, 1993

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EPA REGION 7 GEOLOGIC RADON POTENTIAL SUMMARY

by

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U.S. Geological Survey

EPA Region 7 includes the states of Iowa, Kansas, Missouri, and Nebraska. For each state, geologic radon potential areas were delineated and ranked on the basis of geologic, soil, housing construction, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction chapter. More detailed information on the geology and radon potential of each state in Region 7 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the four states in EPA Region 7, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Radon levels, both high and low, can be quite localized, and within any radon potential area homes with indoor radon levels both above and below the predicted average will likely be found.

Figure 1 shows the geologic radon potential areas in EPA Region 7. Figure 2 shows average screening indoor radon levels in EPA Region 7 by county. The data for each state are from the State/EPA Residential Radon Survey and reflect screening charcoal canister measurements. Figure 3 shows the geologic radon potential of areas in Region 7, combined and summarized from the individual state chapters. Many rocks and soils in EPA Region 7 contain ample radon source material (uranium and radium) and have soil permeabilities sufficient to produce moderate or high radon levels in homes. The following sections summarize the geologic radon potential of each of the four states in Region 7. More detailed discussions may be found in the individual state radon potential chapters for the states in Region 7.

IOWA

Pre-Illinoian-age glacial deposits cover most of Iowa, and are at or near the surface in the southern, northwestern, and much of the northeastern parts of the state. These deposits generally consist of calcium-carbonate-rich loam and clay loam till containing pebbles and cobbles of granite, gabbro, basalt, rhyolite, greenstone, quartzite, chert, diorite, and limestone. Pre-Illinoian tills are covered by from less than 1 m to more than 20 m of Wisconsinan loess (windblown silt) in western, southern, and eastern Iowa. Illinoian glacial deposits occur a relatively small area along the Mississippi River in southeastern Iowa. These deposits consist of loamy to locally sandy till containing clasts of limestone and dolomite, with lesser amounts of igneous and metamorphic rocks, sandstone, and coal fragments. Illinoian deposits are covered by 1-5 m of loess. Wisconsinan drift is represented by the Cary and Tazewell drifts, consisting of calcareous loamy till containing clasts of shale, limestone, and dolomite, with minor amounts of basalt, diabase, granite, chert, and sandstone. Cary drift (now called the Dows Formation), which represents deposits of the Des Moines lobe, is generally not loess-covered; Tazewell drift is covered by as much as 2 m of loess.

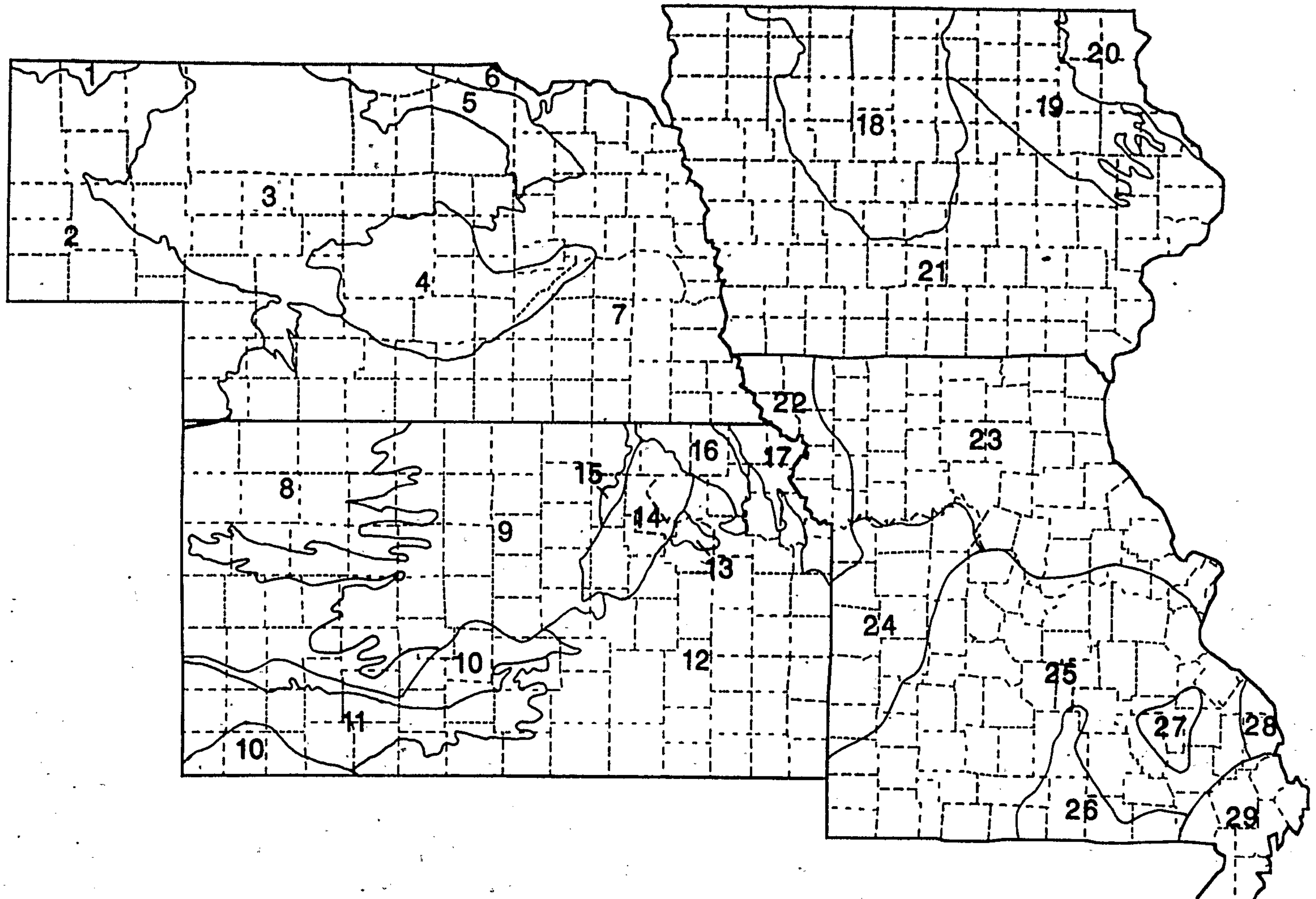


Figure 1. Geologic radon potential areas of EPA Region 7. See text for discussion of areas. 1, 6–Pierre Shale; 2, 5–Tertiary sedimentary rocks; 3–Sand Hills; 4, 8, 11–Tertiary sedimentary rocks covered by varying thicknesses of loess; 7, 13, 16, 21, 23–loess-covered glacial drift plains; 9–Cretaceous sedimentary rocks covered by varying thicknesses of loess; 10–dune sands in the Arkansas and Cimarron river valleys; 12, 15–area underlain by Pennsylvanian and Permian rocks; 14–part of the Mid-Continent Rift Zone; 17, 22–loess and glacial deposits along the Missouri River; 18–Des Moines lobe; 19–Iowan Surface; 20–Paleozoic Plateau; 24–unglaciated part of the Osage Plain; 25–Ozark Plateau; 26, 28–Area underlain by carbonate rocks; 27–St. Francois Mountains; 29–Coastal Plain.

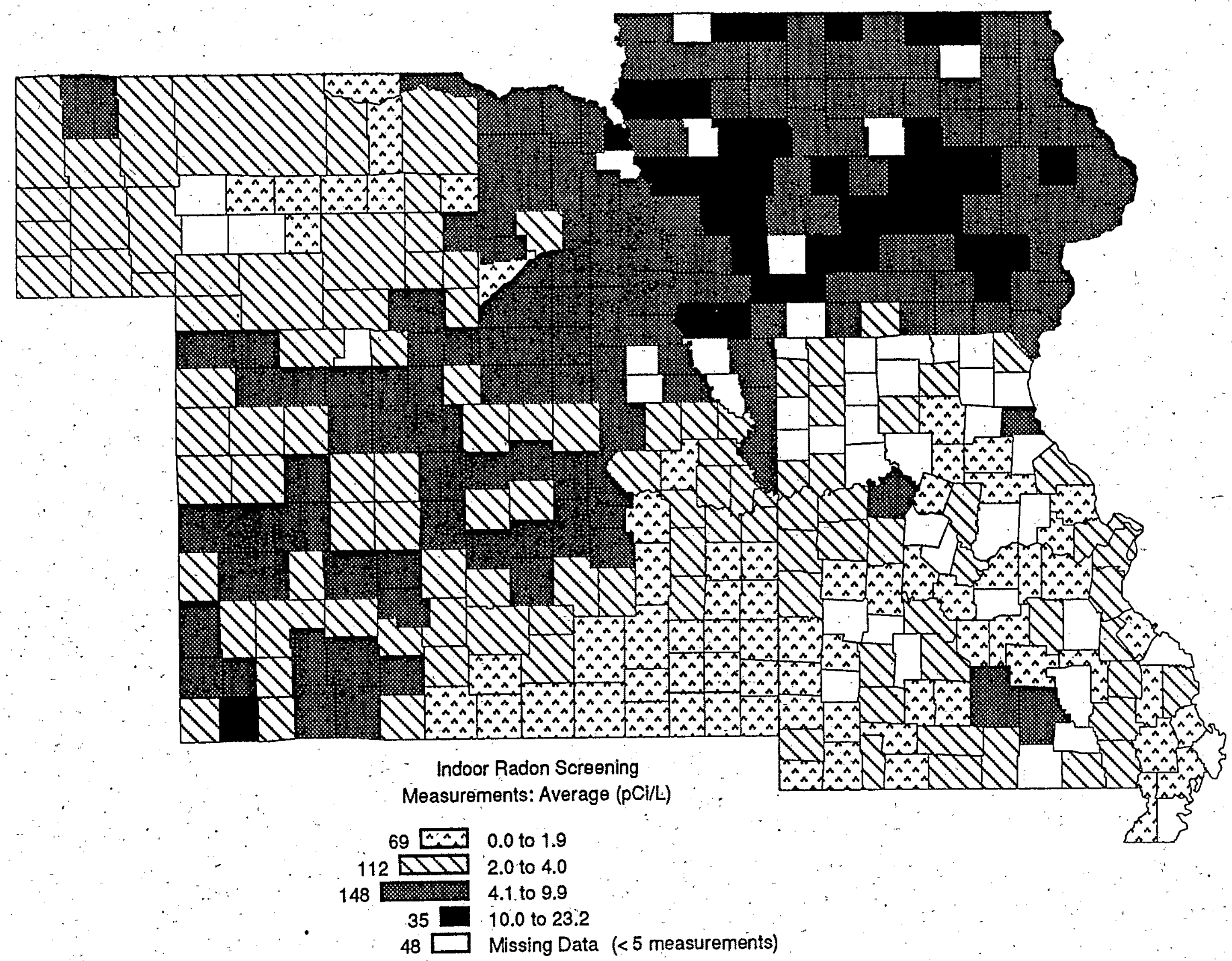


Figure 2. Average screening indoor radon levels by county for EPA Region 7. Data from the State/EPA Residential Radon Survey. Histograms in map legend indicate the number of counties in each measurement category.

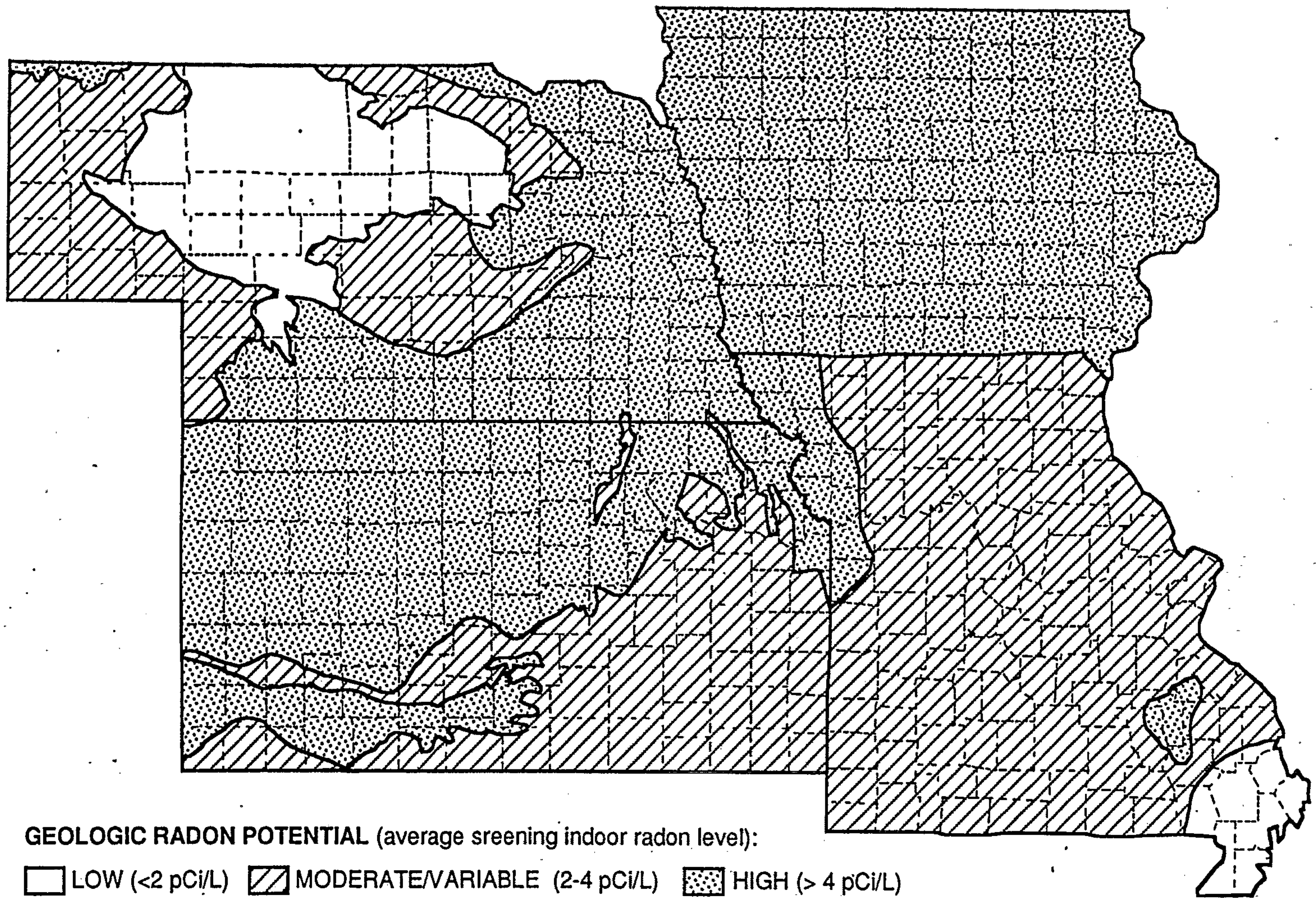


Figure 3. Geologic radon potential of EPA Region 7. Ranges next to each category label indicate the predicted average screening indoor radon level for all homes in each area.

The aeroradioactivity signature of surface deposits in Iowa, especially the Des Moines lobe deposits and other areas in which the loess cover is dicontinuous or absent, seems lower than would be expected in light of the elevated indoor radon levels. This may be because much of the radium in the near-surface soil horizons may have been leached and transported downward in the soil profile, giving a low surface radiometric signature while generating significant radon at depth (1-2 m? or greater) to produce elevated indoor radon levels. For example, a large area of low radioactivity (<1.5 ppm eU) in the northern part of the State corresponds roughly to the Des Moines lobe and the Iowan erosion surface, an area directly east of the Des Moines lobe in northeastern Iowa that is underlain by Pre-Illinoian glacial deposits and loess. However, these areas have high geologic radon potential. Most of the remainder of the State has eU values in the 1.5-2.5 ppm range. In general, soils developed from glacial deposits can be more rapidly leached of mobile ions than their bedrock counterparts, because crushing and grinding of the rocks by glacial action gives soil weathering agents (mainly moisture) better access to soil and mineral grain surfaces. Grinding of the rocks increases the mobility of uranium and radium in the soils by exposing them at grain surfaces, enhancing radionuclide mobility and radon emanation. In addition, poorly-sorted glacial drift may in many cases have higher permeability than the bedrock from which it is derived. Cracking of clayey glacial soils during dry periods can create sufficient permeability for convective radon transport to occur. This may be an important factor causing elevated radon levels in areas underlain by clay-rich glacial deposits.

Loess-covered areas have a higher radiometric signature than loess-free areas, and also appear to correlate roughly with higher average indoor radon levels than loess-free areas, although all areas of Iowa have average indoor radon levels exceeding 4 pCi/L. The Loess-Covered Drift Plains, which cover northwestern Iowa and all of southern Iowa, are underlain by Pre-Illinoian and Illinoian glacial deposits, and loess. The Loess-Covered Drift Plains have overall high radon potential. Valley bottoms with wet soils along the Mississippi and Missouri Rivers may have locally moderate to low radon potential because the gas permeability of the soils is extremely low due to the water filling the pore spaces.

The Paleozoic Plateau, in northeastern Iowa, is underlain primarily by Ordovician carbonate and Cambrian sandstone bedrock covered by varying amounts of Quaternary glacial deposits and loess. It was originally thought to have been unglaciated because it is deeply dissected and lacks glacial landforms. However, small patches of Pre-Illinoian drift have been preserved on uplands, indicating that at least part of the area had been glaciated. The Paleozoic Plateau also has high geologic radon potential. Soils developed from carbonate rocks are derived from the residue that remains after dissolution of the calcium carbonate that makes up the majority of the rock, including heavy minerals and metals such as uranium, and thus they may contain somewhat higher concentrations of uranium or uranium-series radionuclides than the parent rock. Residuum from weathered carbonate rocks may be a potential radon source if a structure is built on such a residual soil, or if the residuum constitutes a significant part of a till or other surficial deposit. In some areas underlain by carbonate bedrock, solution features such as sinkholes and caves increase the overall permeability of the rocks in these areas and generally increase the radon potential of these rocks, but few homes are built directly over major solution features.

KANSAS

Almost all of the bedrock exposed at the surface in Kansas consists of sedimentary units ranging in age from Mississippian to Quaternary. Igneous rocks native to Kansas and exposed at the surface are small localized exposures of Cretaceous lamproite in Woodson County and Cretaceous kimberlite in Riley County. Sedimentary rocks of Mississippian age underlie the extreme southeastern corner of the State. They consist primarily of limestones but also include shale, dolomite, chert, sandstone, and siltstone. Pennsylvanian rocks underlie approximately the eastern one-quarter of the State. They consist of an alternating sequence of marine and nonmarine shale, limestone, sandstone, and coal, with lesser amounts of chert and conglomerate. The shales range from green and gray (low organic content) to black (organic rich). Permian rocks are exposed in east-central and southern Kansas and consist of limestone, shale, gypsum, anhydrite, chert, siltstone, and dolomite. Red sandstone and shale of Permian age underlie the Red Hills along the southern border of Kansas.

The Mississippian, Pennsylvanian, and Permian rocks in eastern Kansas have relatively low uranium contents, generally low to moderate permeability and have generally low to moderate geologic radon potential. Homes situated on Pennsylvanian and Permian carbonate rocks (limestones and dolomites) may have locally elevated indoor radon levels if the limestones have developed clayey residual soils and(or) if solution features (karst topography), are present in the area. Because of the geologic variability of these units, the Mississippian, Pennsylvanian, and Permian rock outcrop area has been ranked moderate or variable in overall geologic radon potential. Homes sited on Pennsylvanian black shale units may be subject to locally high indoor radon levels. This may be the case in the Kansas City area, part of which is underlain by black shales.

Some elevated indoor radon levels in the northern part of the Permian outcrop area, specifically in Marshall, Clay, Riley, Geary, and Dickinson Counties, may be related to faults and fractures of the Mid-Continent Rift and Nemaha Uplift. Many of the subsurface faults reach and displace the surface sedimentary rock cover, and the density and spacing of faults and fractures within the rift zone is relatively high. Fault and shear zones are commonly areas of locally elevated radon because these zones typically have higher permeability than the surrounding rocks, because they are preferred zones of uranium mineralization, and because they are potential pathways through which uranium-, radium-, and(or) radon-bearing fluids and gases can migrate.

Cretaceous sedimentary rocks underlie much of north-central and central Kansas, and consist of green, gray, and black shale, sandstone, siltstone, limestone, chalk, and chalky shale. A discontinuous layer of loess of varying thickness covers the Cretaceous rocks in many areas, particularly in the western part of the Cretaceous outcrop area. Cretaceous rocks in Kansas contain sufficient uranium to generate elevated indoor radon levels. Soils developed on Cretaceous rocks have low to moderate permeability, but the shale-derived soils with low permeability to water likely have moderate permeability to soil gas when they are dry due to desiccation cracks. Areas underlain by these rocks have an overall high radon potential. Tertiary rocks cover much of western Kansas, though they are covered by loess deposits in many areas. Tertiary rocks consist of nonmarine sandstone, siltstone, and shale; volcanic ash deposits; and unconsolidated gravel, sand, silt, and clay. Areas underlain by the Tertiary Ogallala Formation have a moderate radioactivity signature and a moderate to high radon potential.

Loess ranging from 0 to more than 30 meters in thickness covers as much as 65 percent of the surface of Kansas and is thickest and most extensive in the western and north-central parts of the State and in proximity to glacial deposits in the northeastern corner of the State. Possible sources for the loess include: (1) glacial outwash, (2) sand dunes in the Arkansas and Cimarron River valleys or elsewhere (such as the Sand Hills of Nebraska), and (3) erosion of Tertiary sedimentary rocks by wind and rivers. Radon potential of loess-mantled areas depends on the thickness and source of the loess. In areas of very thin loess cover, the radon potential of the underlying bedrock is significant, and the loess both generates radon and transmits radon from the underlying bedrock, whereas if the loess is more than 7-10 m thick, it is probably the sole radon source for homes in the area. Loess-covered areas underlain by Cretaceous and Tertiary bedrock appear to have variably moderate to high radon potential across the State, and locally elevated indoor radon levels may be expected anywhere within areas underlain by these units. Areas underlain by loess-covered Pennsylvanian and Permian rocks appear to generate mainly moderate to locally elevated indoor radon levels.

Areas of windblown sand in the Arkansas and Cimarron River valleys have low uranium contents and low radon potential, but few homes are built directly on the sand dunes. The dune sands are intermixed with loess in parts of the Arkansas and Cimarron valleys, and the radon potential may be related to the relative proportions of sand, loess, and bedrock within these areas. Areas underlain by dune sand are expected to have lower radon levels, areas with considerable loess content are expected to have moderate to locally elevated radon levels. Where sand or loess is thin or absent, the radon levels in homes on Tertiary or Cretaceous bedrock are also expected to generally fall into the moderate to high category.

The area within the glacial limit in northeastern Kansas is underlain by discontinuous glacial drift and loess. The glacial deposits consist of a clay, silt, or sand matrix with cobbles and boulders of igneous and metamorphic rocks derived from as far away as the Lake Superior Region and southwestern Minnesota. The glacial deposits are discontinuous and till thickness varies markedly within the area, most likely because post-glacial erosion has removed and redistributed significant amounts of drift. Because the loess in this area is likely derived from nearby glacial drift, and because glacial deposits are known to generate elevated indoor radon levels throughout the northern Great Plains, this area should be considered to have a moderate to locally high radon potential.

MISSOURI

Missouri lies within the stable midcontinent area of the United States. The dominant geologic feature is the Ozark uplift in the southeastern part of the state which forms the Ozark Plateau Province. Precambrian crystalline rocks form the core of the uplift and crop out along its eastern side. Paleozoic sedimentary rocks dip away from this core in all directions. To the north, northwest, and west of the uplift these sedimentary sequences are folded into broad arches and sags. The Precambrian core of the Ozark uplift is primarily granite and rhyolite. Much of this rock is slightly enriched in uranium (2.5-5.0 ppm). The Precambrian core is surrounded by Cambrian and Ordovician sandstone, dolostone, shale, cherty dolostone, chert, and limestone. Pennsylvanian sandstone, shale and clay crop out in the north-central part of the uplift. To the north and west of the uplift, Mississippian and Pennsylvanian shale, limestone, sandstone, clay, coal, and fire clay occur. Silurian and Devonian sedimentary rocks crop out in central Missouri along the Missouri River and along the Mississippi River northeast of St. Louis and in Cape Girardeau and Perry Counties south of St. Louis.

Uraniferous granites and rhyolites, and residuum developed on carbonate rocks in the Ozark Plateau Province are likely to have significant percentages of homes with indoor radon levels exceeding 4 pCi/L. The most likely areas are those where elevated eU values occur. Where structures are sited on somewhat excessively drained soils in this area the radon potential is further increased. Extreme indoor radon levels may be expected where structures are sited on uranium occurrences and where the disturbed zone around a foundation is connected to solution openings in carbonate rocks or to open zones in soil and bedrock caused by mine subsidence.

The Ozark Plateau Province has a moderate overall radon potential. Several areas of somewhat excessively drained soils, scattered uranium occurrences, residual carbonate soils in which uranium has been concentrated, and areas of karst may generate locally elevated indoor radon levels in this area. The St. Francois Mountains have high radon potential owing to elevated levels of uranium in soils developed on granitic and volcanic rocks throughout these mountains and substantial areas of somewhat excessively to excessively drained soils.

The permeability of soils and subsoils in karst areas has been enhanced by solution openings in and near carbonate pinnacles and by zones of solution collapse. Where soils developed on such carbonate rocks are thin, foundations may encounter open bedrock fractures in the limestone. Karst underlies parts of the City and County of St. Louis and may locally cause elevated indoor radon levels. Elevated eU and significant karst development occur in Perry and Cape Girardeau Counties. Structures sited on locally highly permeable karst soils with elevated eU in these two counties will likely have elevated indoor radon levels. Broad karst areas have formed by dissolution of carbonate rocks in the central and western Ozark Plateau, the southern Osage Plain, and along the Mississippi River from Cape Girardeau County to Ralls County. These carbonate regions have overall moderate radon potential. However, areas of intense karst development, elevated uranium in residual soils developed on carbonate, and large areas of somewhat excessively drained to excessively drained soils may cause locally high indoor radon levels to occur.

Several very thin, highly uraniferous (as much as 180 ppm), black, phosphatic shales occur in the Devonian and Pennsylvanian sedimentary rock sequences in the unglaciated Osage Plain of southwestern Missouri. Elevated indoor radon levels may be expected where the foundations of structures intercept the thin Pennsylvanian uraniferous shales or the Chattanooga Shale in the southwestern part of the state from Kansas City south to McDonald and Barry Counties and in north-central Missouri in Boone, Randolph and Macon Counties, or where they intercept well-drained alluvium derived from these rocks. Because these uraniferous shales are so thin, such circumstances are likely to be very site- or tract-specific; thus detailed geologic and soil mapping will be necessary to outline areas of potential problems. Where these shales are jointed or fractured or soils formed on them are somewhat excessively drained on hillslopes, the radon potential is further increased. Residuum developed on limestones associated with these uraniferous shales may also have elevated uranium levels and have significant radon potential. The unglaciated Osage Plain province has a low overall radon potential; however, areas of thin soils underlain by the uraniferous shales in this province have high radon potential with locally extreme values possible.

Along the Missouri and Mississippi River valley floor, alluvial deposits (silt, sand, and gravel) dominate. Loess deposits occur on the flanks of the river valleys in several areas and are especially widespread in Platte, Buchanan, Holt, and Atchison Counties along the Missouri River north of Kansas City. Alluvium and loess along the upper Missouri River Valley upstream from Kansas City seem to be producing elevated indoor radon levels that may be related to the somewhat elevated uranium content of these materials and, possibly, to elevated radon emanation and diffusion associated with well-drained loess deposits. Detailed studies of indoor radon data in this area would be necessary to determine more closely the origin of elevated indoor radon levels. Thin, somewhat excessively drained soils developed on limestone that occur as part of one soil association in the southern suburbs of Kansas City may also be related to elevated indoor radon levels in Jackson County.

The northernmost part of the Mississippi Embayment occupies the southeastern corner of the state and forms the Coastal Plain Province, or southeastern lowlands. This area is underlain by Tertiary and Quaternary alluvium. The Coastal Plain Province has a low radon potential overall. Only one value exceeding 4 pCi/L is reported for a six-county area, and very poorly drained soils are widespread. However, some aeroradiometric anomalies occur in this area, and some excessively drained soils occur locally. Elevated indoor radon levels may be associated with these locales. Although elevated eU occurs over some of the sedimentary rocks in this province, the high soil moisture, the very poorly drained soils, and the low indoor radon values all point towards low radon potential.

The surficial geology north of the Missouri River is dominated by glacial deposits covered with a thin veneer of loess; however, several areas of residual soils developed on underlying sedimentary rocks occur in the eastern and western parts of this region. Residual soils are those soils formed by weathering of the material beneath the soil. These surficial deposits (both glacial deposits and residuum) are generally 50-200 feet thick, but they locally exceed 200 feet along the northern edge of the state. The dissected till plain of northern Missouri has moderate overall radon potential, although elevated indoor radon levels are common in areas of similar geology in adjacent states, particularly Iowa, Nebraska (fig. 1), and Illinois. Except for counties along the Missouri River, the indoor radon data for the counties in the dissected till plain are sparse and appear to be generally in the low to moderate range.

NEBRASKA

Rocks ranging in age from Pennsylvanian to Quaternary are exposed in Nebraska. Pennsylvanian rocks are exposed in southeastern Nebraska and include limestones, shales, and sandstones. Only some of the Upper Pennsylvanian strata are exposed in Nebraska; these rocks are a repeated sequence of marine shales and limestones alternating with nonmarine sandstones and shales, and thin coals. Exposed Permian rocks consist of green, gray, and red shales, limestone, and gypsum. Exposures of Pennsylvanian and Permian rocks are generally limited to valley sides along streams because much of the eastern part of the State is mantled with Pleistocene glacial deposits and loess. Black shales of Pennsylvanian age may constitute a significant radon source where the shales are a source component of the glacial tills.

Cretaceous rocks are exposed in much of eastern Nebraska, in parts of northern and northwestern Nebraska, and along the Republican River Valley. Lower Cretaceous rocks consist of sandstones, shales, and thin coals. Upper Cretaceous rocks consist primarily of shale, limestone, and sandstone. The Upper Cretaceous Pierre Shale consists of gray, brown, and black shales, with thin layers of bentonite, chalk, limestone, and sandstone. Although the permeability of soils developed on the Pierre Shale is listed as low, the shales contain numerous fractures and partings and are likely to have sufficient permeability for radon transport during dry periods. The stratigraphically lowest unit in the Pierre Shale is the Sharon Springs Member, a black shale of widespread occurrence in Nebraska, South Dakota, Kansas, and Colorado. The Sharon Springs Member is exposed in a relatively broad area along the Niobrara and Missouri Rivers from Keya Paha to Cedar Counties and along the Republican River in southern Nebraska. The gray-shale units of the Pierre Shale, while not as uraniferous as the black shale of the Sharon Springs Member, generally contain higher-than-average (i.e., >2.5 ppm) amounts of uranium and are correlated with elevated indoor radon levels in several areas. Outcrops of the Pierre Shale in the northwestern corner of Nebraska have the highest surface radioactivity in the State. Areas underlain by Cretaceous rocks, particularly the Pierre Shale, have overall high radon potential.

Tertiary rocks have the most widespread exposure in the State. The White River Group consists of mudstone, siltstone, sandstone, and thin layers of volcanic ash, and is exposed in the North and South Platte valleys and in northwestern Nebraska. The Arikaree Group overlies the White River Group and consists of siltstone and sandstone. The Tertiary Ogallala Group covers about two-thirds of the State. It consists of sandstone, siltstone, gravel, sand, silt, clay, and thin volcanic ash layers. The Ogallala is covered by the Sand Hills, an area of Quaternary windblown sand deposits, in the north-central part of Nebraska. Pre-Sand Hills sediments of Pliocene and Quaternary age also overlie portions of the Ogallala in this area. The Ogallala, Arikaree, and White River Groups all have high surface radioactivity (for purposes of this report, high radioactivity is defined as greater than 2.5 ppm eU) and are known to host uranium deposits. Soils developed on the Tertiary units have moderate permeability and generate moderate to locally high indoor radon. The White River and Arikaree Groups have significant amounts of uranium-bearing volcanic glass and may be somewhat more likely to generate elevated indoor radon concentrations. Areas underlain by Tertiary sedimentary rocks have overall moderate radon potential. Some homes in this area are likely to have high indoor radon levels, particularly those sited on uranium-bearing parts of the White River and Arikaree Groups in northwestern Nebraska.

Eastern Nebraska and southern Nebraska south of the Platte River are underlain by Permian through Tertiary rocks mantled with Pleistocene glacial deposits of Pre-Illinoian age and loess. The glacial deposits generally consist of a clay, silt, or sand matrix with pebbles and cobbles of limestone, igneous rocks, and quartzite. Source material for the glacial deposits includes locally-derived Permian and Pennsylvanian limestone and shale and Cretaceous sandstone and shale, as well as lesser amounts of sandstone, limestone, shale, and igneous and metamorphic rocks from bedrock sources to the north and northeast. Of the source rocks underlying the glacial deposits and those to the north and northeast, Cretaceous sandstones and shales, Pennsylvanian black shales, and Precambrian crystalline rocks all contain sufficient amounts of uranium-series radionuclides (uranium and(or) radium) to generate radon at elevated levels.

Loess covers most of the glacial deposits in eastern Nebraska as well as bedrock in the south-central part of the State. Loess is a generally good radon source because it consists of silt and clay-sized particles, which are more likely to be associated with radionuclides and have higher emanation coefficients than larger sized particles, and it typically has moderate permeability. Average indoor radon levels are consistently greater than 4 pCi/L in areas underlain by loess-mantled glacial drift. The majority of homes in the area underlain by loess-mantled bedrock in the south-central part of the State also have radon levels exceeding 4 pCi/L, but indoor radon levels are likely to be more variable from house to house in south-central Nebraska, depending on the distribution, thickness, or weathering extent of the loess. Areas underlain by glacial drift and most areas underlain by loess have overall high radon potential. The area mapped as loess between the Platte River and the Sand Hills in the central part of the State has generally moderate radon potential. Homes sited on thicker loess along the north side of the Platte River in Dawson and Buffalo Counties may have locally high indoor radon levels. The Sand Hills have low surface radioactivity and generally low radon potential.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF IOWA

by
R. Randall Schumann
U.S. Geological Survey

INTRODUCTION

Many of the rocks and soils in Iowa have the potential to generate levels of indoor radon exceeding the U.S. Environmental Protection Agency's guideline of 4 pCi/L. In a survey of 1381 homes conducted during the winter of 1988-89 by the Iowa Department of Public Health and the EPA, using short-term charcoal canister screening tests, 71 percent of the homes had indoor radon levels exceeding this value. About 7 percent of the screening measurements exceeded 20 pCi/L. The surficial materials covering most of Iowa are glacial and glacially-derived deposits composed of material from local and distant bedrock sources. Radon at levels of concern can be generated from these deposits in most areas of the state. At the scale of this evaluation, all areas of Iowa are considered to have high radon potential.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Iowa. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Any localized assessment of radon potential must be supplemented with additional data and information from the locality. Within any area of a given radon potential ranking, there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon levels, both high and low, can be quite localized, and there is no substitute for testing individual homes. Elevated levels of indoor radon have been found in every state, and EPA recommends that all homes be tested. For more information on radon, the reader is urged to consult the local or State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

Iowa is part of the Central Lowlands physiographic province and is characterized by a flat to gently rolling landscape. Total relief varies from 146 m (480 ft) in the southeast corner to 509 m (1670 ft) in the northwestern part of Iowa (Prior, 1976). Iowa is subdivided into seven physiographic regions (fig. 1), each having distinct landscape character. The following discussion of physiography is summarized from Prior (1976).

The Paleozoic Plateau, in the northeastern corner of Iowa (fig. 1), was once thought to be completely untouched by Pleistocene glaciers; however, it is now known that at least one glacier entered the region in Pre-Illinoian time (Anderson, 1983). The topography of this area is controlled by the underlying Silurian, Ordovician, and Cambrian bedrock consisting primarily of carbonate rock (limestone and dolomite), sandstone, and shale. Deeply dissected valleys and abundant bedrock outcrops characterize the landscape. Karst topography (sinkholes, caves, and disappearing drainages) occurs locally. The western part of this region is covered with a thin mantle of loess and Pre-Illinoian glacial deposits, although the topography is still largely bedrock-controlled.

Along the southeastern and southwestern edges of the State are the alluvial plains of the Mississippi and Missouri Rivers (fig. 1). These areas are characterized by low-relief alluvial

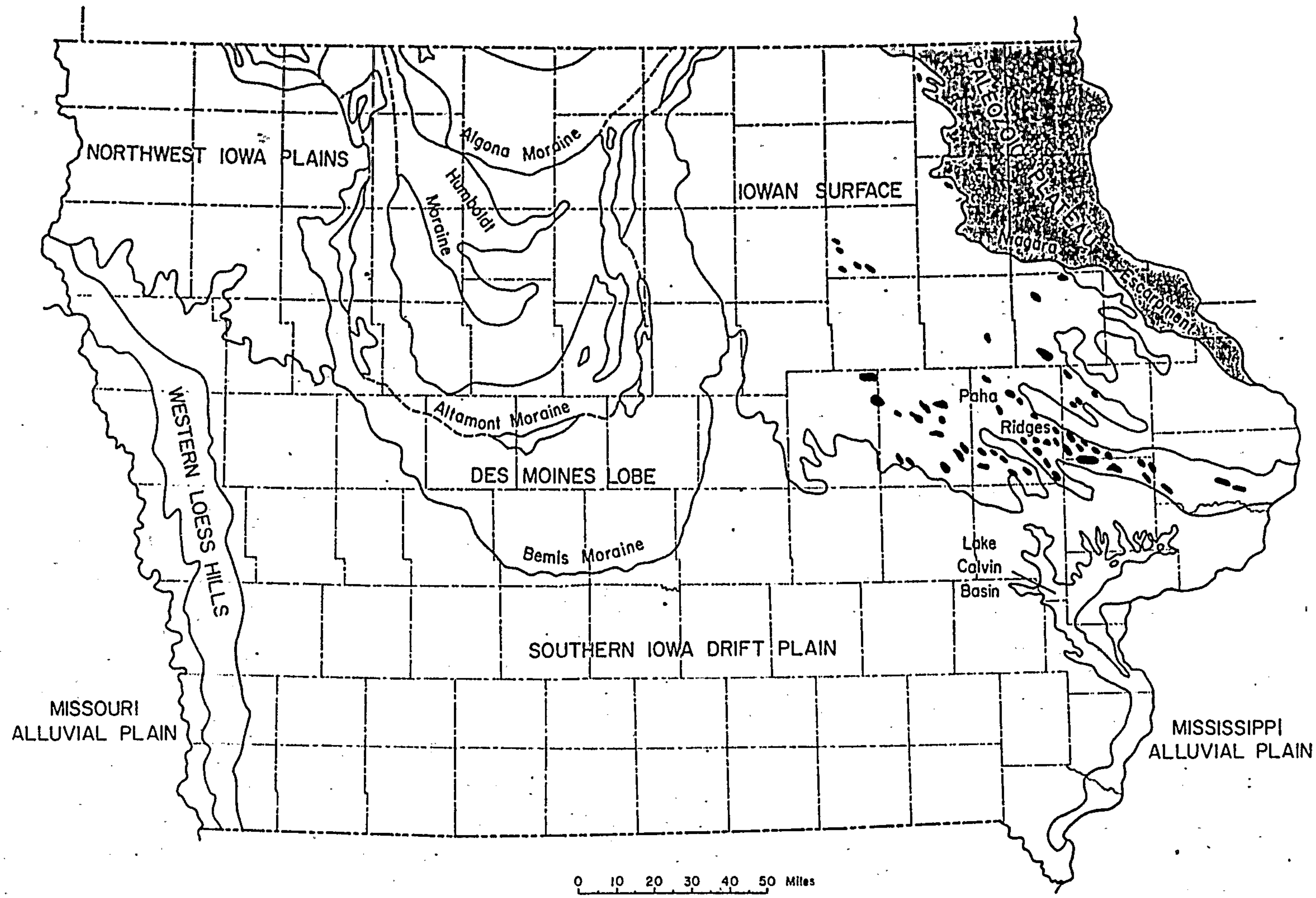


Figure 1. Physiographic regions of Iowa (from Prior, 1976).

plains, terraces, and wetlands. The Western Loess Hills parallel the Missouri River valley (fig. 1). This area is characterized by steep, dissected ridges and hills, and thick loess (windblown silt) deposits.

The Southern Iowa Drift Plain covers most of the southern half of Iowa. Disecction of the gently sloping surface by streams produced the rolling to hilly terrain.

The Northwest Iowa Plains is similar to the High Plains of the Dakotas. This area of loess-mantled, gently rolling landscapes is higher, drier, and less wooded than any other part of Iowa.

The topography of the Des Moines Lobe of north-central Iowa (fig. 1) consists of glacial landforms, including knob and kettle topography, end moraines, eskers, and lakes. It is one of the few areas of the state not covered by loess.

The Iowan Surface is a distinctive topographic region in northeastern Iowa. The land surface is level to gently rolling with long slopes and low relief. The gradual progression from drainage divides to stream valleys gives this area a gently stepped appearance. Loess cover in this region is thin and discontinuous. In the southern third of the Iowan Surface, prominent elongate ridges and isolated elliptical hills of loess, called paha, are common. Karst features have developed in small, localized areas where limestone bedrock is close to the surface.

Iowa is divided into 99 counties (fig. 2). Most of the State's population is rural. Counties with populations exceeding 50,000 are those that include major metropolitan areas, such as Woodbury (Sioux City), Pottawattamie (Council Bluffs), Polk (Des Moines), Black Hawk (Waterloo), Linn (Cedar Rapids), Dubuque (Dubuque), and Scott (Quad Cities) (fig. 3).

GEOLOGY

The geology discussion is divided into three sections: bedrock geology, glacial geology, and the occurrence of uranium in rocks and soils. A bedrock geologic map (fig. 4) shows rock units that underlie glacial deposits or are exposed at the surface in some areas. The glacial deposits are composed of material derived from underlying bedrock and from rock units to the north, northwest, and east. The discussion of bedrock geology is summarized from Anderson (1983) and Iowa Geological Survey (1969). The section on glacial geology is summarized from Wright and Ruhe (1965), Hallberg (1980), and Richmond and others (1991). The reader is encouraged to consult these and other reports for more detailed discussions and maps than presented herein.

Bedrock geology: Rocks ranging in age from Precambrian to Cretaceous underlie the glacial deposits in Iowa. Most of these are sedimentary rocks, including limestone, shale, siltstone, and sandstone, of marine and nonmarine origin. A small area of Precambrian granite directly underlies the glacial deposits in southeastern Pocahontas County (fig. 4). Outcrops of the Precambrian Sioux Quartzite, a pink to red, tightly cemented, quartz sandstone that is the oldest rock exposed in the State, occur in the northwestern corner of Iowa.

Cambrian rocks, primarily sandstones, and Ordovician carbonate rocks (limestones and dolomites), sandstone, and shale are exposed in northeastern Iowa, and Ordovician rocks also directly underlie glacial deposits in other parts of the State (fig. 4). Glauconite is found in several of the Cambrian rock units but is especially abundant in the Lone Rock Formation, in which it has formed "greensands", named for the green color of the glauconite. The Ordovician Maquoketa Formation contains phosphatic dolomites and iron-rich shales. Karst features, including sinkholes, disappearing streams, and caves are common in upland outcrop areas of the Ordovician Galena Group in northeastern Iowa.

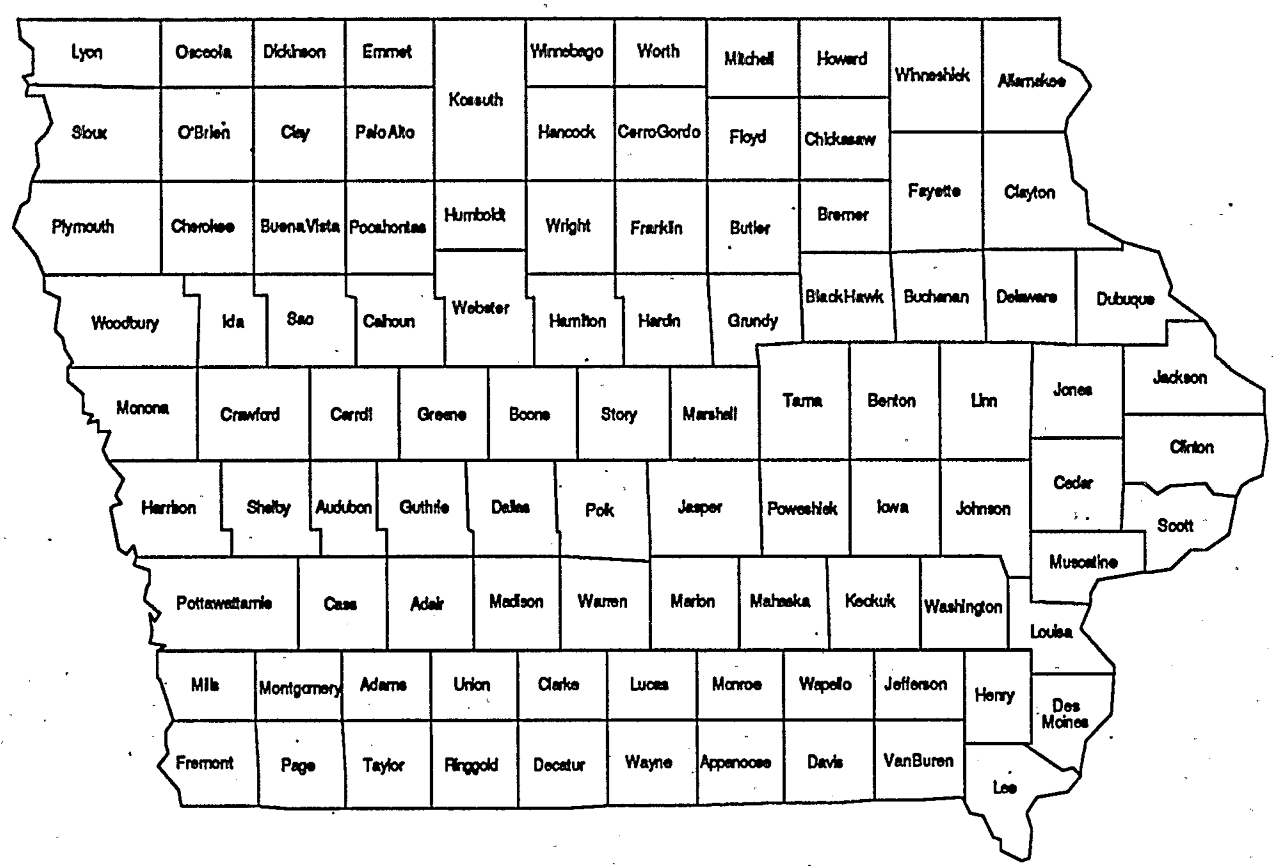


Figure 2. Iowa counties.

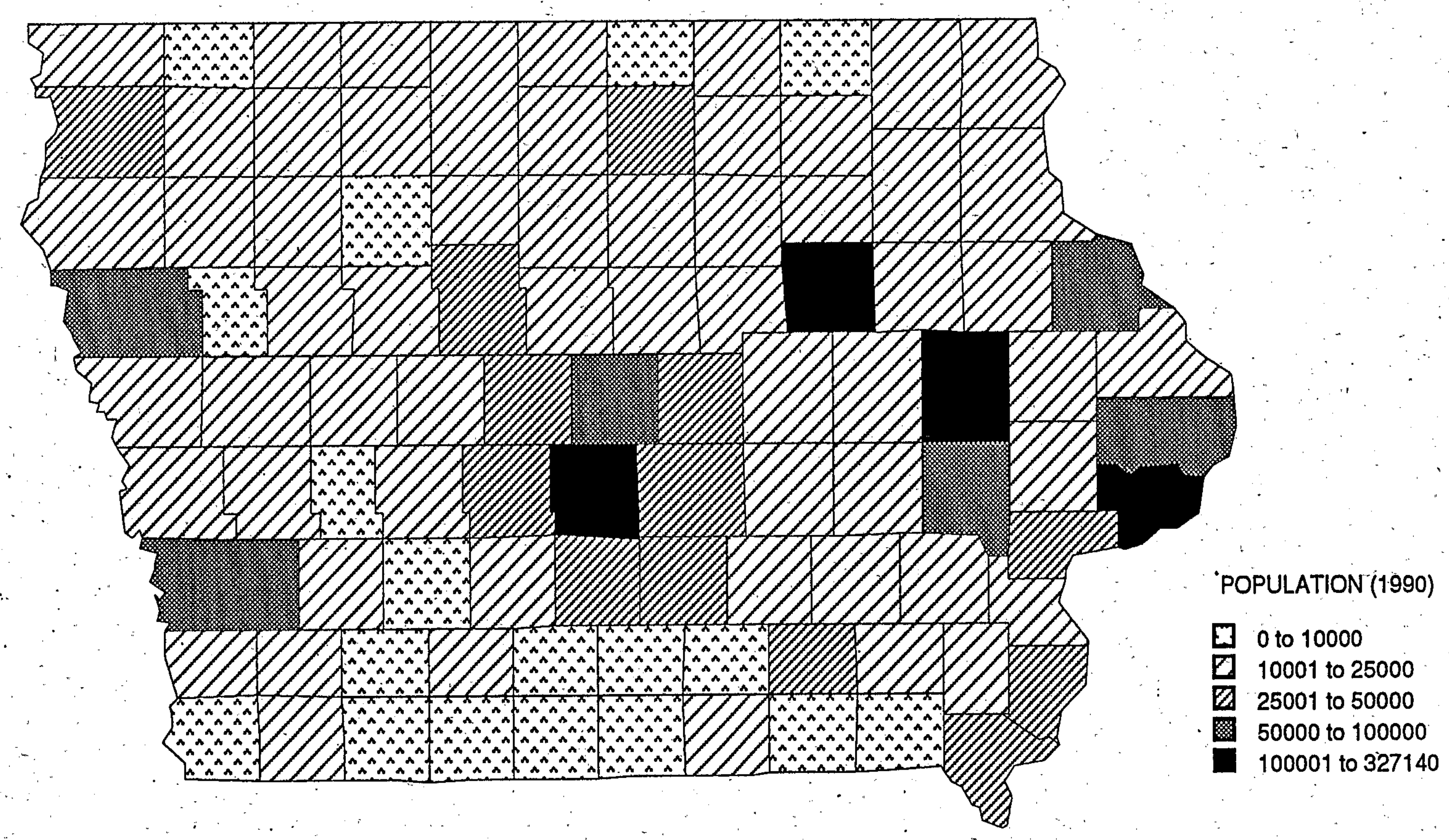


Figure 3. Population of counties in Iowa (1990 U.S. Census data).

Figure 4. Generalized bedrock geologic map of Iowa (after Iowa Geological Survey, 1969).

Generalized Geologic Map of Iowa
Explanation

Cretaceous

Shale, limestone, and sandstone.

Jurassic

Fort Dodge Beds - Gypsum, red and green shales.

Pennsylvanian

Virgil - Alternating shale and limestone.

Missouri - Alternating shale and limestone with some thin coal beds.

Des Moines - Alternating limestone and shale with some sandstone, thin limestones, and coal.

Mississippian

Shale, limestone, sandy limestone, oolitic limestone, dolomite, cherty dolomite, and siltstone.

Devonian

Upper - Siltstone, shale, dolomite, and limestone.

Middle - Limestone and dolomites, shales in middle.

Silurian

Dolomite, cherty dolomite, and sandy dolomite.

Ordovician

Dolomite, shale, chert, limestone, sandstone, sandy and cherty dolomite.

Cambrian

Sandstone, dolomite, glauconitic sandstone, siltstone, and shale.

Precambrian

Sediments (sandstones), igneous, and metamorphic rocks.

SYSTEM	SERIES	GROUP	FORMATION
QUATERNARY	Pleistocene		
	Holocene Ep.		DeForest
	Wisconsin Ep.		Peoria Loess
			Dows
			Noah Creek
			Sheldon Creek
			Roxana Silt / Pisgah
			St. Charles
	Illinoian Ep.		Glasford
	Pre-Illinoian		Wolf Creek
			Alburnett
TERTIARY			Unnamed alluvial deposits
			"Fullerton"
			"Elk Creek"
			Unnamed alluvial deposits
CRETACEOUS			Pierre
			Niobrara
			Carlile Sh.
			Greenhorn Ls.
			Graneros Sh.
			Dakota / Windrow
JURASSIC			Fort Dodge
PENNSYLVANIAN	Virgilian	Wabaunsee	Wood Siding
			Root
			Stotler
			Pillsbury
			Zeandale
			Willard Sh.
			Emporia
			Auburn Sh.
			Bern
			Scranton
			Howard Ls.
			Severy Sh.
		Shawnee	Topeka
			Calhoun Sh.
			Deer Ck.
			Tecumseh Sh.
			Lecompton
			Kanwaka Sh.
			Oread
		Douglas	Lawrence
			Stranger
	Missourian	Lansing	Stanton
			Vilas Sh.
			Plattsburg
		Kansas City	Lane-Bonner Spring Sh.
			Wyandotte
			Liberty Memorial Sh.
			Iola
			Chanute Sh.
			Dewey
			Nellie Bly Sh.
			Cherryvale
		Bronson	Dennis
			Galesburg Sh.
			Swope
			Ladore Sh.
			Hertha
			Pleasanton
	Desmoinesian	Marmaton	Lost Branch
			"Memorial" Sh.
			Lenapah
			Nowata Sh.
			Altamont

Figure 4 (continued). Stratigraphic column of Iowa, showing names, ages, and relative positions of rock units in the State (from Iowa Geological Survey, 1992).

SYSTEM	SERIES	GROUP	FORMATION
PENNSYLVANIAN			Bandera Sh.
			Pawnee
			Labette
			Stephens Forest
			Morgan School Sh.
			Mouse Ck.
		Cherokee	Swede Hollow
			Floris
			Spoon
	Atokan		Kalo
			Kilbourn
	Morrowan		Caseyville
MISSISSIPPIAN	Chesterian		
	Meramecian		Pella (Ste. Genevieve)
			St. Louis
			"Spergen"
			Warsaw
	Osagean		Keokuk
			\ Burlington
	Kinderhookian		Gilmore City \
			"Maynes Creek"
		North Hill	"Chapin"
			Starrs Cave
			Prospect Hill
			McCraney
DEVONIAN	Upper	"Yellow Spring"	Maple Mill
			Aplington
			Sheffield
			Lime Creek / Sweetland Creek
		Cedar Valley	Shell Rock
			Lithograph City
	Middle		Coralville
			Little Cedar
		Wapsipinicon	Pinicon Ridge
			Otis / Spillvile
			Bertram
SILURIAN			Gower
			Scotch Grove \ Laporte
			Hopkinton \ City
			Waucoma
			Blanding
			Tete des Morts
			Mosalem
ORDOVICIAN	Upper		Maquoketa
		Galena	Dubuque
			Wise Lake
	Middle		Dunleith
			Decorah
			Platteville
		Ancell	Glenwood
			St. Peter Ss.
	Lower	Prairie du Chien	Shakopee
			Oneota
CAMBRIAN	Upper		Jordan
			St. Lawrence
		Tunnel City	Lone Rock
			Adel
			Wonewoc
			Bonneterre
			Eau Claire
			Mt. Simon
PROTEROZOIC			
ARCHEAN			

Figure 4 (continued). Stratigraphic column of Iowa (from Iowa Geological Survey, 1992).

Silurian rocks in Iowa consist almost entirely of dolomite and underlie glacial deposits in eastern Iowa, except where they are exposed in the valleys of the Maquoketa, Wapsipinicon, Cedar, and Mississippi rivers. Solution features such as sinkholes occur in Silurian rocks in some areas of eastern Iowa.

Devonian rocks, consisting of limestone, dolomite, and shale, underlie glacial deposits in a northwest-southeast trending band in east-central Iowa (fig. 4). In southeastern Iowa the Devonian Sheffield Formation consists of dark gray and black shale. Mississippian rocks include limestone and dolomite with lesser amounts of sandstone, siltstone, and shale. Chert is a common constituent of several Mississippian carbonates.

Pennsylvanian rocks occur beneath the glacial cover in the central and south-central part of the State. The Pennsylvanian strata consist of interbedded sequences of shale, siltstone, claystone, coal, and limestone. Coal deposits of economic potential are found in rocks of the Pennsylvanian Cherokee, Marmaton, and Wabaunsee Groups. Some of the Pennsylvanian shales are carbonaceous, or organic-rich (black shales). Thick beds of Pennsylvanian sandstone form cliffs at Ledges and Dolliver State Parks, northwest of Des Moines, and at Wildcat Den State Park east of Muscatine.

Permian and Triassic rocks are absent in Iowa, and Jurassic rocks are represented only by exposures of the Fort Dodge Formation in Webster County, which consists of gypsum, red, gray, and green shale, and minor beds of sandstone and conglomerate.

Cretaceous rocks underlie northwestern and west-central Iowa (fig. 4) and include sandstone, shale, conglomerate, coal, and limestone. Isolated exposures of Cretaceous iron-oxide-cemented (limonitic) sands and gravels occur in Allamakee County in northeast Iowa, but they are too small to be shown on figure 4.

Glacial geology: Pre-Illinoian (formerly called "Nebraskan" and "Kansan") glacial deposits cover most of Iowa, and are at or near the surface in the southern, northwestern, and much of the northeastern parts of the state (fig. 5a). These deposits generally consist of calcareous (calcium-carbonate-rich) loam and clay loam till containing pebbles and cobbles of granite, gabbro, basalt, rhyolite, greenstone, quartzite, chert, diorite, and limestone. Igneous and metamorphic rocks become less abundant in the till as one moves southward; limestone, dolomite, and chert become more abundant in south-central Iowa and limestone and shale become more abundant in southwestern Iowa. Several Pre-Illinoian till units are recognized in Iowa; most of the tills are separated by paleosols (buried soils). Pre-Illinoian tills are covered by a variable thickness of Wisconsinan loess in western, southern, and eastern Iowa (fig. 5b).

Illinoian glacial deposits occur in a relatively small area along the Mississippi River in southeastern Iowa. These deposits consist of loamy to locally sandy till containing clasts of limestone and dolomite, with lesser amounts of igneous and metamorphic rocks, sandstone, and coal fragments. Unlike the Pre-Illinoian and Wisconsinan deposits, which were derived from northern and northwestern sources, Illinoian tills were deposited by the Lake Michigan lobe, which moved from northeast to southwest across Illinois, terminating in eastern Iowa. Illinoian deposits are covered by 1-5 m of loess.

Wisconsinan drift is represented by the Cary and Tazewell drifts (fig. 5a), consisting of calcareous loamy till containing clasts of shale, limestone, and dolomite, with minor amounts of basalt, diabase, granite, chert, and sandstone. Cary drift (now called the Dows Formation) is generally not loess-covered; Tazewell drift is covered by as much as 2 m of loess. Wisconsinan and Pre-Illinoian tills contain significant amounts of expandable clays (smectites).

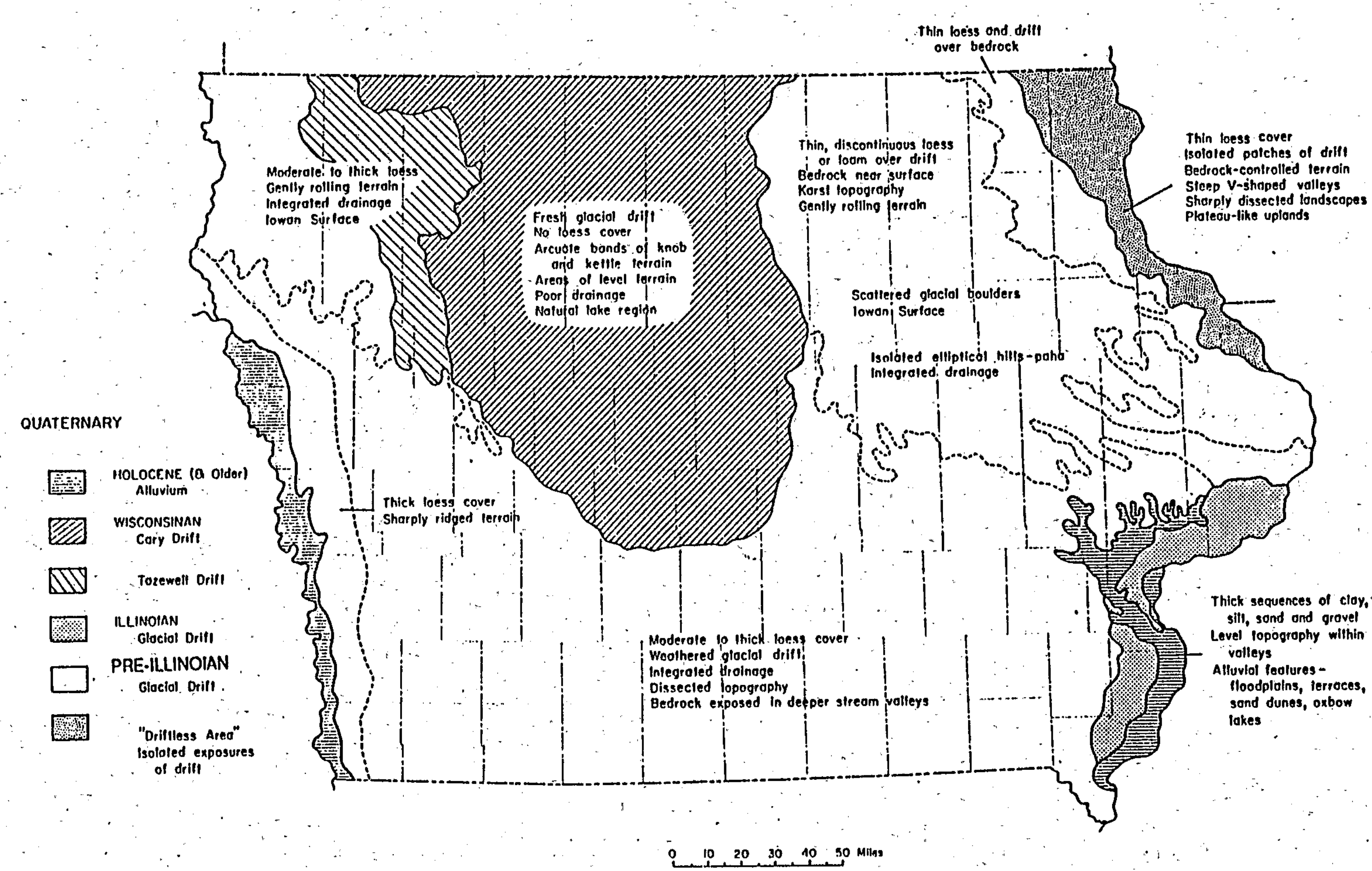


Figure 5a. Glacial features and surface materials map of Iowa (modified from Prior, 1976).

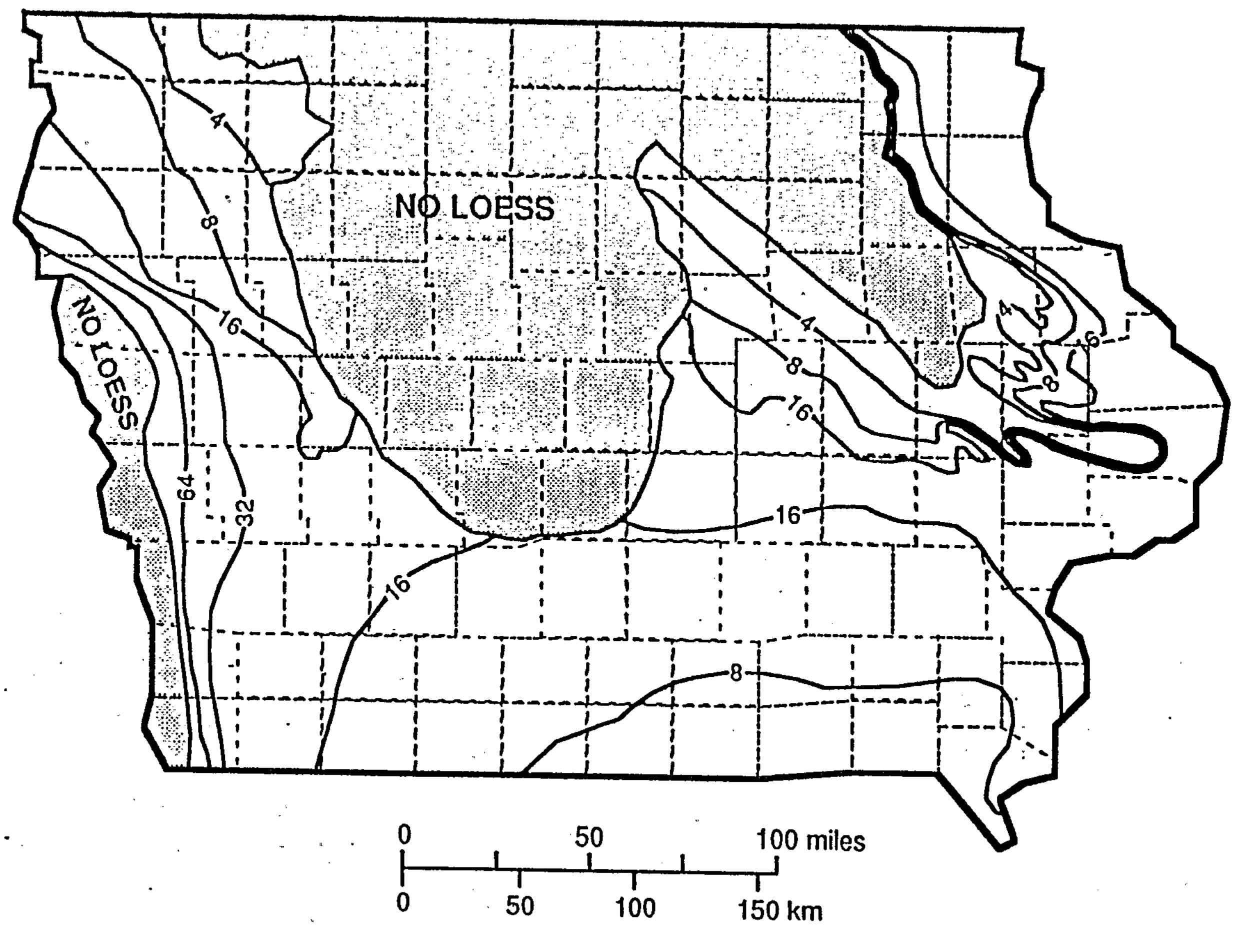


Figure 5b. Loess thickness in Iowa, in feet (after Anderson, 1983).

The Paleozoic Plateau of northeastern Iowa was originally thought to have been unglaciated because it is deeply dissected and lacks glacial landforms, and was formerly called the "Dirftless Area". However, small patches of Pre-Illinoian drift have been preserved on uplands, indicating that at least part of the area had been glaciated (Anderson, 1983).

Uranium geology: No uranium deposits or occurrences of commercial grade are known to exist in Iowa, although uranium deposits of potentially commercial grade may exist in the subsurface at the contact between the Precambrian Sioux Quartzite and underlying igneous and metamorphic rocks in northwestern Iowa (Anderson and Bunker, 1982). However, some rock types in Iowa likely contain sufficient uranium or uranium-series radionuclides to generate radon at levels of concern. Because most of the glacial deposits in Iowa contain a mixture of locally-derived and transported bedrock source components, and because few studies of uranium in tills or loess are known to exist, it is important to consider the occurrence and abundance of radon sources in bedrock in light of the presence and relative abundances of such rocks as source components of the tills.

Black shales are well-known concentrators of uranium and are known causes of radon problems in a number of areas in the United States. Uranium is concentrated with organic compounds in the shales or in phosphate layers within the shales (Ostrom and others, 1955). Two rock units, the Devonian Sheffield and Maple Mill Formations and the Pennsylvanian Cherokee Group, are identified as containing black shale beds in the subsurface (Iowa Geological Survey, 1969).

Carbonate rocks (limestone, dolomite) may also constitute a source for low-level uranium concentrations. Although the carbonate rocks themselves are low in uranium and radium, soils and residual deposits developed from these rocks are derived from the dissolution of the calcium carbonate that makes up the majority of the rock. As the calcium carbonate is dissolved away, the soils become relatively enriched in the remaining impurities—predominantly base metals, including uranium. Rinds containing relatively high concentrations of uranium and uranium minerals can be formed on the surfaces of rocks involved with calcium carbonate dissolution.

SOILS

Udolls (Mollisols of temperate climates) cover most of Iowa. Most soils in southern Iowa are Agriudolls, moist soils with a subsurface horizon of clay accumulation (U.S. Soil Conservation Service, 1987). Soils in northern Iowa are generally Hapludolls, which generally lack a subsurface horizon of clay accumulation. Hapludalfs, moist soils with a thin subsurface clay horizon, occur along the Mississippi River and its tributaries in eastern Iowa. Most soils of Iowa have loam, sandy loam, silt loam, silty clay loam, or clay loam textures (Oschwald and others, 1965). Soils in the northern half of Iowa generally have moderate permeability, whereas most of the southern half of the State is covered by soils with low permeability (fig. 6).

INDOOR RADON DATA

Indoor radon data from 1381 homes sampled in the State/EPA Residential Radon Survey conducted in Iowa during the winter of 1988-89 are shown in figure 7 and listed in Table 1. The data are derived from short-term (2-7 day) screening measurements using charcoal canister radon detectors placed in the lowest level of the home (in Iowa, usually the basement). Data are only shown on figure 7 for those counties with 5 or more data values. The overall average indoor radon value for the State was 8.9 pCi/L. The maximum value recorded in the survey was 130 pCi/L in

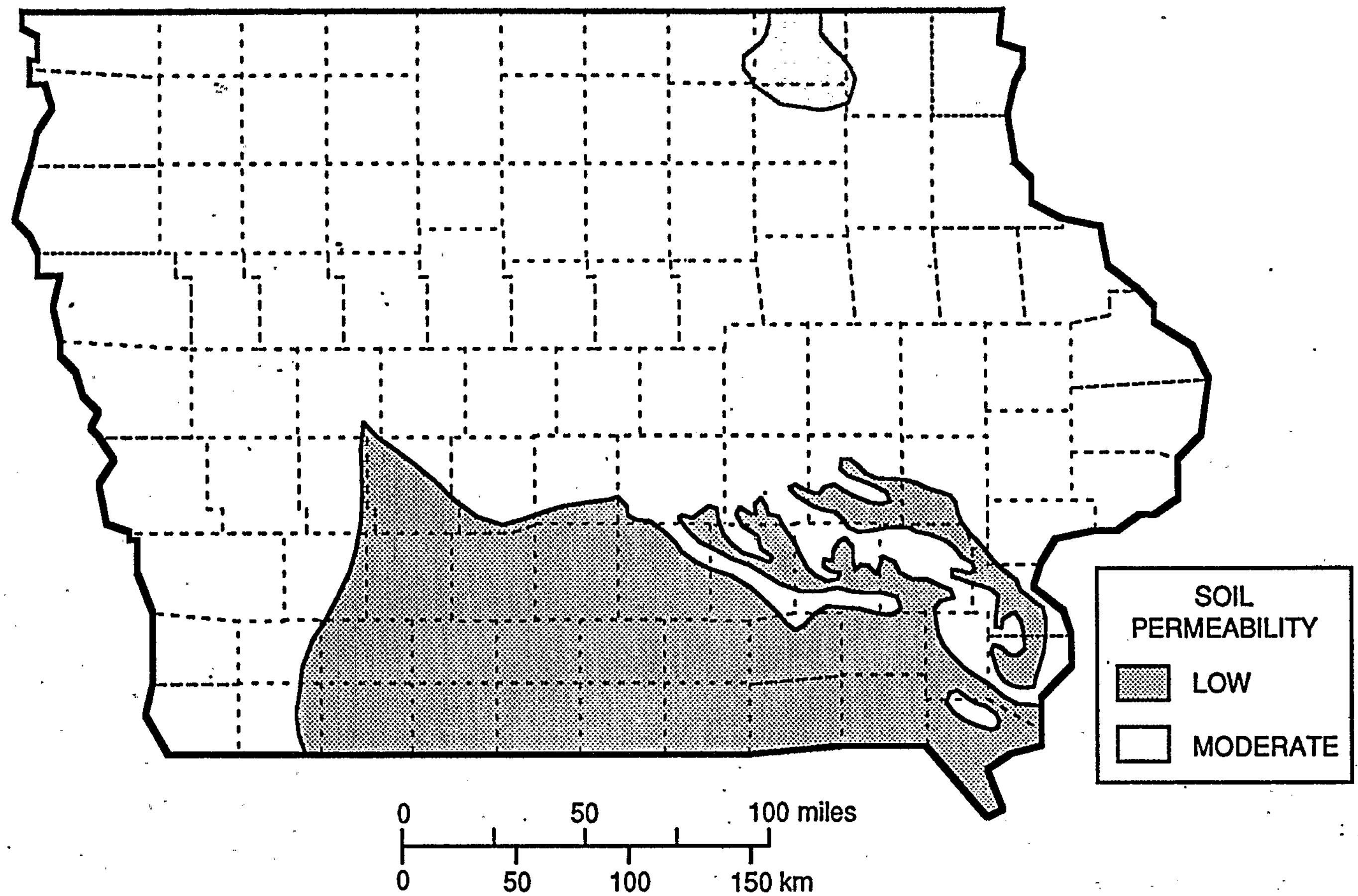
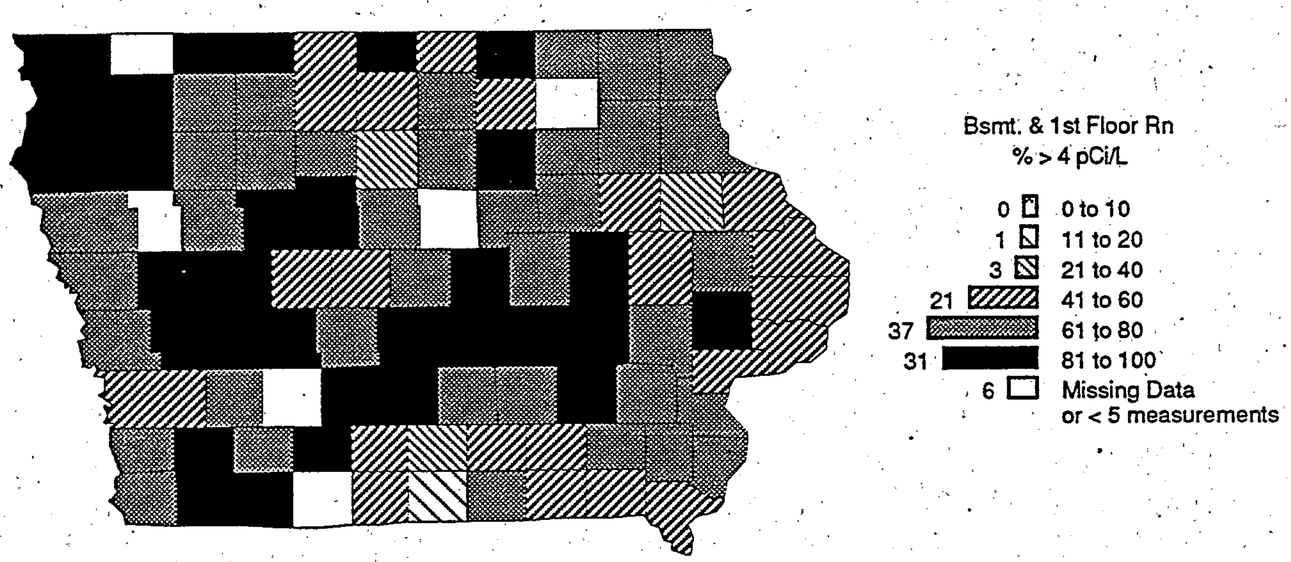


Figure 6. Generalized soil permeability map of Iowa (data from Oschwald and others, 1965).



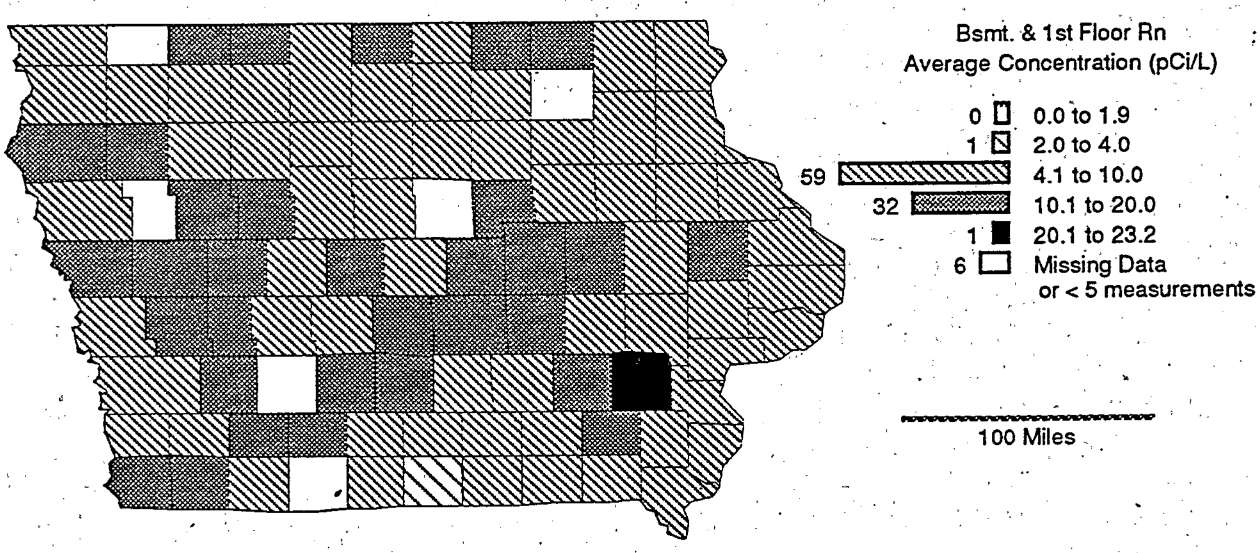


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Iowa, 1988-89, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Iowa conducted during 1988-89. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAIR	3	10.1	6.3	13.1	7.8	15.9	67	0
ADAMS	5	12.8	9.6	12.0	7.6	20.0	80	0
ALLAMAKEE	6	8.1	4.7	9.8	6.1	13.9	67	0
APPANOOSE	13	8.1	5.1	6.3	7.6	30.0	77	8
AUDUBON	6	13.8	13.0	12.6	5.2	21.6	100	17
BENTON	11	12.6	10.7	11.6	8.1	32.3	91	18
BLACK HAWK	55	7.6	5.5	5.6	8.4	53.5	67	5
BOONE	11	11.4	7.0	4.3	12.3	36.5	55	18
BREMER	17	8.3	6.1	5.9	8.8	39.2	65	6
BUCHANAN	14	4.6	3.6	3.8	3.1	10.4	50	0
BUENA VISTA	17	7.1	6.2	7.7	3.6	15.8	76	0
BUTLER	17	8.4	7.0	6.4	5.8	22.0	88	6
CALHOUN	5	11.9	8.6	7.5	12.3	33.5	100	20
CARROLL	17	12.3	10.2	9.6	9.4	42.9	94	12
CASS	14	10.8	8.8	8.3	6.6	23.6	79	7
CEDAR	6	7.9	6.3	8.8	4.3	12.4	83	0
CERRO GORDO	24	6.7	5.1	4.3	5.4	19.6	63	0
CHEROKEE	15	11.7	10.2	10.5	6.1	27.3	93	7
CHICKASAW	4	5.3	4.3	4.4	3.9	10.5	50	0
CLARKE	9	7.1	4.8	7.0	5.6	15.1	56	0
CLAY	9	7.0	6.0	5.4	4.5	16.3	78	0
CLAYTON	13	8.4	4.8	6.7	9.1	33.5	62	8
CLINTON	15	6.5	3.9	4.8	6.2	22.9	60	7
CRAWFORD	12	10.6	9.7	9.6	5.1	23.2	100	8
DALLAS	10	9.3	6.2	7.3	8.5	27.7	70	10
DAVIS	8	5.8	3.8	4.6	5.5	17.3	50	0
DECATUR	11	6.7	5.0	4.8	7.0	26.7	55	9
DELAWARE	9	4.7	3.7	2.9	3.9	13.0	33	0
DES MOINES	24	8.0	5.8	5.8	6.3	22.1	71	8
DICKINSON	12	10.2	8.6	7.7	6.6	22.6	92	8
DUBUQUE	38	5.6	4.0	5.0	4.7	24.0	58	3
EMMET	11	12.5	7.7	6.1	18.8	68.3	91	9
FAYETTE	11	8.3	5.3	7.2	6.9	22.4	73	9
FLOYD	12	5.0	3.9	4.3	4.4	17.9	58	0
FRANKLIN	17	7.5	6.5	7.9	3.8	15.4	76	0
FREMONT	5	11.9	10.0	13.0	6.4	19.8	80	0
GREENE	8	6.1	3.9	4.6	5.9	18.5	50	0
GRUNDY	6	10.2	7.1	8.2	8.5	24.3	67	17
GUTHRIE	10	9.1	8.0	7.4	4.8	19.9	90	0
HAMILTON	10	7.4	6.0	6.4	5.1	18.6	70	0
HANCOCK	8	4.3	3.4	4.0	2.5	8.1	50	0

TABLE 1 (continued). Screening indoor radon data for Iowa.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HARDIN	4	10.9	9.6	11.2	5.6	16.8	100	0
HARRISON	12	7.1	5.5	4.8	5.1	17.4	67	0
HENRY	7	8.8	7.2	7.2	5.8	18.9	71	0
HOWARD	10	18.5	7.2	6.2	39.3	130.1	70	10
HUMBOLDT	9	9.3	6.7	9.9	6.3	17.2	67	0
IDA	3	10.0	9.5	10.0	3.7	13.7	100	0
IOWA	8	9.0	7.0	8.2	5.5	18.8	88	0
JACKSON	9	9.1	6.2	5.2	9.8	33.0	56	11
JASPER	13	12.5	9.4	11.1	9.9	37.6	85	15
JEFFERSON	13	13.3	5.6	8.8	16.2	59.0	62	23
JOHNSON	16	7.3	5.7	7.0	4.2	15.1	75	0
JONES	8	10.8	6.2	5.5	14.8	46.5	63	13
KEOKUK	7	17.5	11.4	10.9	13.6	35.0	86	43
KOSSUTH	19	5.4	3.7	4.3	4.9	21.1	58	5
LEE	17	5.5	3.9	3.9	4.8	20.5	47	6
LINN	41	6.3	3.7	3.7	7.4	32.6	44	10
LOUISA	8	6.5	5.7	5.8	3.7	13.0	75	0
LUCAS	8	4.3	3.0	2.5	4.3	13.9	38	0
LYON	11	8.4	8.2	8.3	2.3	12.1	100	0
MADISON	11	10.4	8.5	10.4	5.5	23.0	91	9
MAHASKA	12	9.1	7.4	8.5	5.7	19.8	75	0
MARION	33	8.5	4.9	7.5	7.0	30.5	67	9
MARSHALL	10	10.5	9.7	10.9	4.3	16.9	100	0
MILLS	12	9.2	6.9	8.1	8.0	31.1	67	8
MITCHELL	6	13.0	11.2	12.8	7.2	21.3	100	33
MONONA	10	10.2	8.8	10.4	5.2	21.0	80	10
MONROE	11	5.8	4.3	3.6	4.6	14.7	45	0
MONTGOMERY	7	9.5	8.8	9.4	3.7	14.1	100	0
MUSCATINE	20	6.4	4.1	4.4	6.4	23.0	60	10
O'BRIEN	13	9.1	8.2	8.1	3.9	15.9	92	0
OSCEOLA	4	7.0	6.5	5.9	3.4	11.9	100	0
PAGE	17	10.9	8.6	10.8	7.1	30.2	82	12
PALO ALTO	10	7.1	5.6	7.8	4.2	14.7	70	0
PLYMOUTH	15	16.4	11.4	9.2	15.3	49.9	87	20
POCAHONTAS	6	8.1	6.4	5.8	6.1	17.7	67	0
POLK	77	11.4	8.4	8.8	8.2	45.6	86	12
POTTAWATTAMIE	45	6.3	4.4	5.0	4.7	20.4	56	2
POWESHIEK	12	15.9	8.8	12.8	11.5	37.4	92	33
RINGGOLD	3	15.0	14.5	13.2	4.9	20.5	100	33
SAC	9	11.4	9.1	10.9	8.7	32.2	78	11
SCOTT	35	8.2	5.2	6.7	8.5	47.4	60	6
SHELBY	14	12.4	10.6	12.3	6.6	25.2	93	14
SIOUX	21	8.6	7.9	8.1	3.3	14.2	90	0

TABLE 1 (continued). Screening indoor radon data for Iowa.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
STORY	19	7.8	5.9	6.8	6.1	25.9	68	5
TAMA	8	11.3	8.0	8.9	8.9	27.0	75	25
TAYLOR	6	9.6	8.4	8.1	5.4	19.0	83	0
UNION	11	10.3	8.6	9.2	5.9	21.3	82	9
VAN BUREN	7	8.3	5.7	8.7	6.5	17.2	57	0
WAPELLO	15	7.7	5.2	4.1	10.2	42.8	53	7
WARREN	29	13.5	8.4	9.2	19.2	106.9	86	10
WASHINGTON	7	23.2	8.5	9.8	33.0	92.8	71	29
WAYNE	6	2.5	1.6	2.4	1.9	5.1	17	0
WEBSTER	11	6.7	6.1	5.9	3.1	13.0	91	0
WINNEBAGO	10	10.4	9.1	8.0	6.4	25.9	90	10
WINNESHIEK	10	8.6	6.1	5.6	7.5	25.7	70	10
WOODBURY	62	9.1	6.0	6.9	9.5	65.4	71	6
WORTH	6	8.3	4.7	3.7	10.2	27.7	50	17
WRIGHT	10	7.0	4.1	3.6	7.5	25.2	40	10

Howard County. Only 7 percent of the homes tested in the state had indoor radon levels exceeding 20 pCi/L. Except for Wayne County, which had a screening indoor radon average of 2.5 pCi/L, every county for which data are shown in figure 7 had an indoor radon average greater than 4 pCi/L in the State/EPA survey.

Long-term radon measurements on the main floors of 213 homes in central and eastern Iowa yielded geometric means of 2.1 pCi/L in central Iowa and 1.6 pCi/L in the eastern part of the State (Wiffenbach and Hart, 1990). Significant differences in radon levels among different categories of homes were attributed to differences in ventilation rates, basement construction, and extent of cracks and openings in basement floors and walls. Fifty homes with private wells were also tested for radon in water, yielding an average radon concentration of 490 pCi/L, a geometric mean of 350 pCi/L, and a maximum radon concentration of 1700 pCi/L (Wiffenbach and Hart, 1990).

GEOLOGIC RADON POTENTIAL

An aerial radiometric map of Iowa (fig. 8) shows gamma radioactivity of surficial deposits and soils. A large area of low (< 1.5 ppm) equivalent uranium (eU) in the northern part of the State corresponds roughly to the Des Moines lobe and the Iowan erosion surface. Most of the remainder of the State has eU values in the 1.5-2.5 ppm range (fig. 8). Areas of eU greater than 2.5 ppm occur in the east-central and west-central parts of the State (fig. 8), but do not appear to correlate with specific surface features. The eU signature of surface deposits in Iowa, especially the Des Moines lobe deposits and other areas of thin loess cover (fig. 5b), seems lower than would be expected in light of the elevated indoor radon levels. Recent studies (for example, Lively and others, 1991; Schumann and others, 1991) suggest that much of the radium in the near-surface soil horizons may have been leached and transported downward in the soil profile, giving a low surface radiometric signature while generating significant radon at depth (1-2 m? or greater) to produce elevated indoor radon levels. In general, soils developed from glacial deposits can be more rapidly leached of mobile ions than their bedrock counterparts, because crushing and grinding of the rocks by glacial action gives soil weathering agents (mainly moisture) better access to soil and mineral grain surfaces (Jenny, 1935). Grinding of the rocks increases the mobility of uranium and radium in the soils by exposing them at grain surfaces, enhancing radionuclide mobility and radon emanation. In addition, poorly-sorted glacial drift may in many cases have higher permeability than the bedrock from which it is derived. Cracking of clayey glacial soils during dry periods can create sufficient permeability for convective radon transport to occur. This may be an important factor causing elevated radon levels in areas underlain by clay-rich glacial deposits. Loess-covered areas have a higher radiometric signature than loess-free areas, and also appear to correlate roughly with higher average indoor radon levels than loess-free areas, although all areas of Iowa have average indoor radon levels exceeding 4 pCi/L.

Areas underlain by carbonate bedrock in the northeastern part of the state also have high geologic radon potential. As discussed in the uranium section of this report, soils developed from carbonate rocks are derived from the residue that remains after dissolution of the calcium carbonate that makes up the majority of the rock, including heavy minerals and metals such as uranium, and thus they may contain somewhat higher concentrations of uranium or uranium-series radionuclides than the parent rock. Residuum from weathered carbonate rocks may be a potential radon source if a structure is built on such a residual soil, or if the residuum constitutes a significant part of a till or other surficial deposit. In some areas underlain by carbonate bedrock, solution features such as

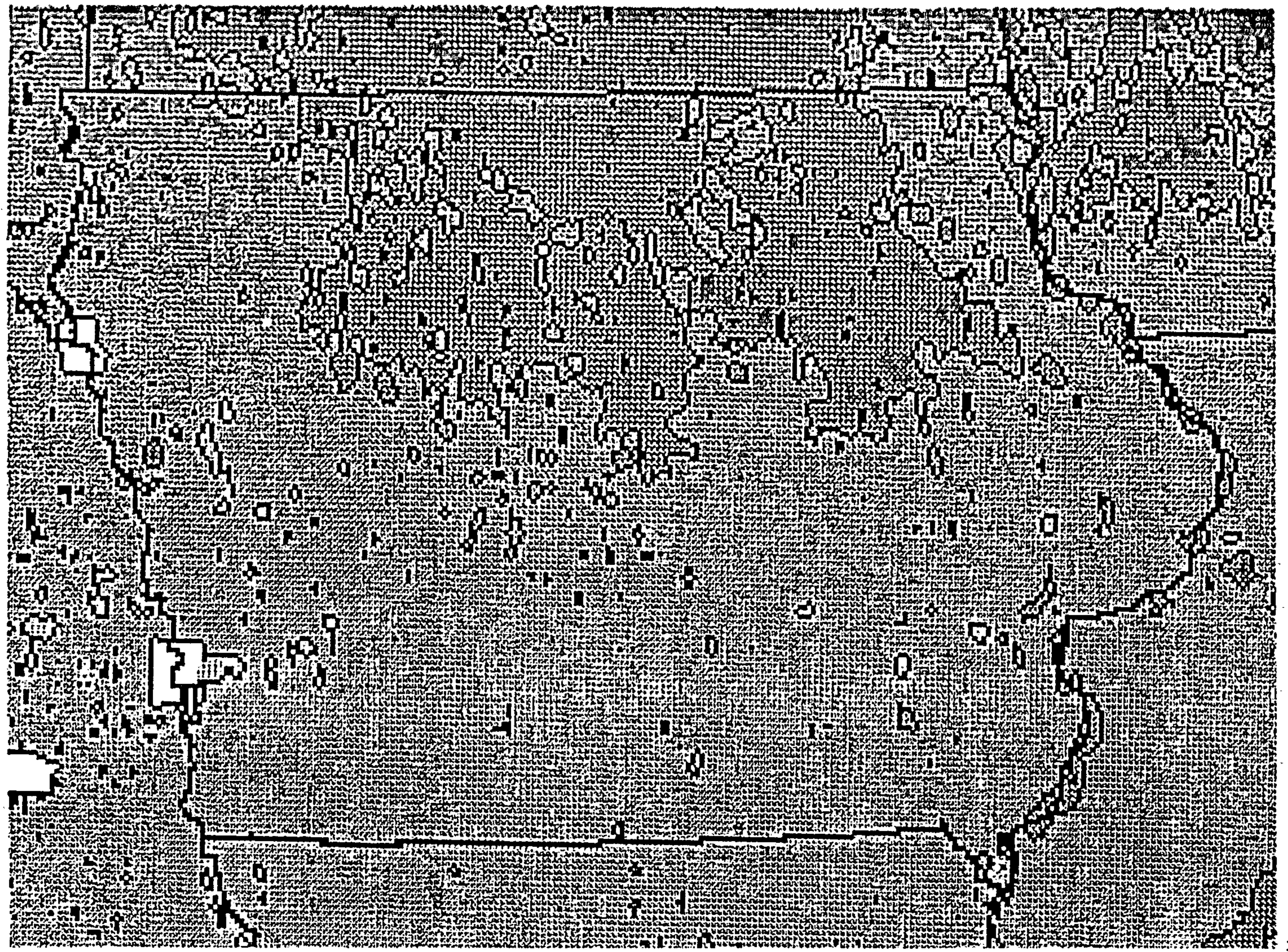


Figure 8. Aerial radiometric map of Iowa (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

sinkholes and caves increase the overall permeability of the rocks in these areas and generally increase the radon potential of these rocks, but these features provide unstable foundations for building construction, so homes are generally not built in such areas.

RADON INDEX AND CONFIDENCE INDEX SCORES

For the purposes of this assessment, Iowa is divided into four geologic radon potential areas (fig. 9) and each area assigned Radon Index (RI) and Confidence Index (CI) scores (Table 2). The Radon Index is a semiquantitative measure of radon potential based on geologic, soil, and indoor radon factors, and the Confidence Index is a measure of the relative confidence of the RI assessment based on the quality and quantity of data used to make the predictions (see the Introduction chapter for more information on the methods and data used).

The Des Moines Lobe is underlain by Wisconsinan-age loam tills. It has a high radon potential (RI=12) with high confidence (CI=10).

The Iowan Surface is underlain by Pre-Illinoian glacial deposits and loess. As shown in figure 9, the Iowan Surface radon potential area includes only that part of the Iowan Surface that is covered by less than 4 ft of loess (see figure 5b). The Iowan Surface has a high radon potential (RI=12) with high confidence (CI=10).

The Paleozoic Plateau is underlain primarily by Ordovician carbonate and Cambrian sandstone bedrock covered by varying amounts of Quaternary glacial deposits and loess. This area has a high radon potential (RI=13) with high confidence (CI=10).

The Loess-Covered Drift Plains (fig. 9) covers the remainder of the State, and is underlain by Pre-Illinoian and Illinoian glacial deposits, and loess. Valley bottoms with wet soils along the Mississippi and Missouri Rivers may have locally moderate to low radon potential because the gas permeability of the soils is extremely low due to the water filling the pore spaces. The Loess-Covered Drift Plains has an overall high radon potential (RI=13) with high confidence (CI=10).

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential that assigned to the area as a whole. Any local decisions about radon should <u>not</u> be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. Radon Index (RI) and Confidence Index (CI) scores for geologic radon potential areas of Iowa. See figure 9 for locations of areas.

	AREA							
	Des Moines Lobe		Iowan Surface		Paleozoic Plateau		Loess-covered Drift Plains	
FACTOR	RI	CI	RI	CI	RI	CI	RI	CI
INDOOR RADON	3	3	3	3	3	3	3	3
RADIOACTIVITY	1	2	1	2	2	2	2	2
GEOLOGY	3	3	3	2	3	2	3	2
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	3	--	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--	0	--
TOTAL	12	10	12	10	13	10	13	10
RANKING	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

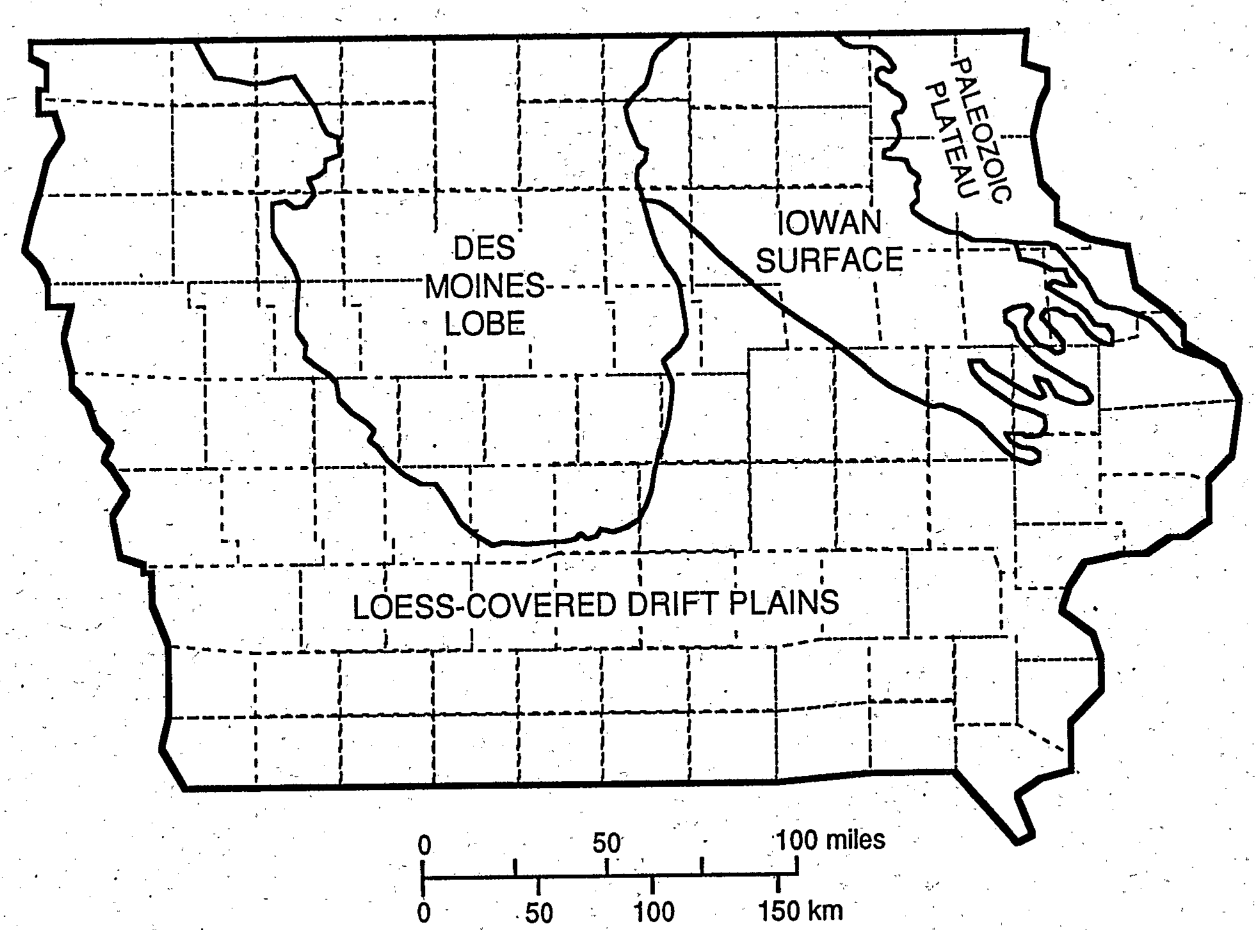


Figure 9. Geologic radon potential areas of Iowa. See Table 1 for radon potential scores of areas.

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EPA's Map of Radon Zones

The USGS' Geologic Radon Province Map is the technical foundation for EPA's Map of Radon Zones. The Geologic Radon Province Map defines the radon potential for approximately 360 geologic provinces. EPA has adapted this information to fit a county boundary map in order to produce the Map of Radon Zones.

The Map of Radon Zones is based on the same range of predicted screening levels of indoor radon as USGS' Geologic Radon Province Map. EPA defines the three zones as follows: Zone One areas have an average predicted indoor radon screening potential greater than 4 pCi/L. Zone Two areas are predicted to have an average indoor radon screening potential between 2 pCi/L and 4 pCi/L. Zone Three areas are predicted to have an average indoor radon screening potential less than 2 pCi/L.

Since the geologic province boundaries cross state and county boundaries, a strict translation of counties from the Geologic Radon Province Map to the Map of Radon Zones was not possible. For counties that have variable radon potential (i.e., are located in two or more provinces of different rankings), the counties were assigned to a zone based on the predicted radon potential of the province in which most of its area lies. (See Part I for more details.)

IOWA MAP OF RADON ZONES

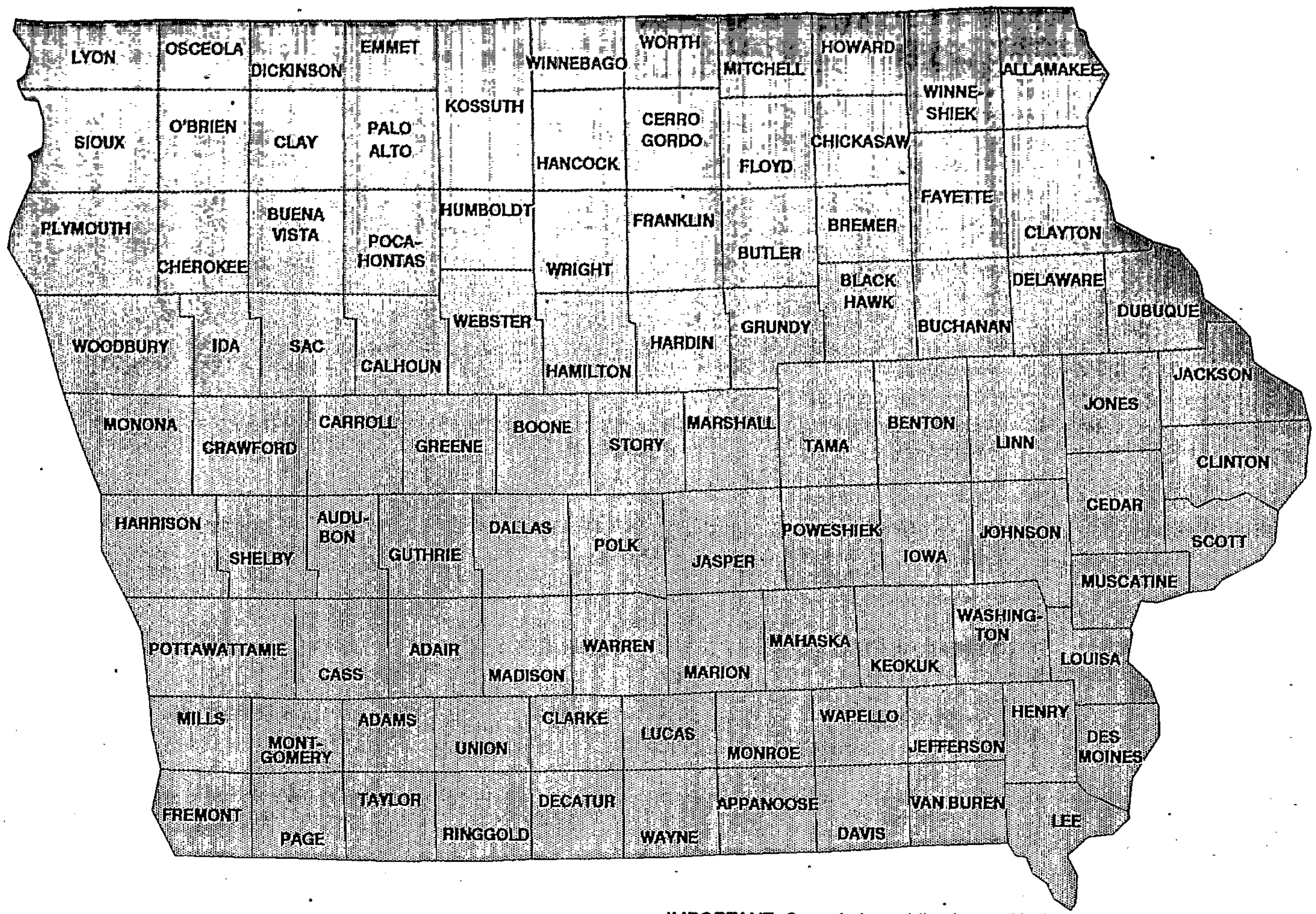
The Iowa Map of Radon Zones and its supporting documentation (Part IV of this report) have received extensive review by Iowa geologists and radon program experts. The map for Iowa generally reflects current State knowledge about radon for its counties. Some States have been able to conduct radon investigations in areas smaller than geologic provinces and counties, so it is important to consult locally available data.

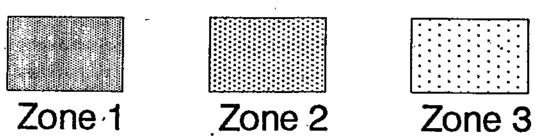
Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of Iowa" -- may appear to be quite specific, it cannot be applied to determine the radon levels of a neighborhood, housing tract, individual house, etc. **THE ONLY WAY TO DETERMINE IF A HOUSE HAS ELEVATED INDOOR RADON IS TO TEST.** Contact the Region 7 EPA office or the Iowa radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

IOWA - EPA Map of Radon Zones

The purpose of this map is to assist National, State and local organizations to target their resources and to implement radon-resistant building codes.

This map is not intended to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. ***All homes should be tested, regardless of zone designation.***





IMPORTANT: Consult the publication entitled "Preliminary Geologic Radon Potential Assessment of Iowa" before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.